

AN ABSTRACT OF THE THESIS OF

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Title: Use of a Geographical Information System to Modify Pheromone Trap-Based  
Predictions of *Helicoverpa zea* (Boddie) Damage.

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The GRASS (V. 4.0) geographical information system (GIS) was used to test the hypothesis that pheromone trap based predictions of *Helicoverpa zea* (Boddie) damage in processed sweet corn could be improved by considering spatial patterns of corn plantings and wind blocking features around the trap. Wind blocking features include: tree rows, wooded areas, large buildings close to the trap, and abrupt hillsides. Pheromone traps were monitored at 29 and 30 sites in 1990 and 1991. Corn development through the year and damage levels at harvest (percent infestation) were also recorded for these locations. Maps of all corn plantings and wind blocking features within 2.5 kilometers of the trap were created, digitized, and entered into the GIS for each site. A stepwise regression analysis considering 18 spatial and two non-spatial variables resulted in a highly significant ( $P < 0.001$ ) four variable regression model with an  $R^2$  of 0.82. Spatial input variables used in this model included the total number of hectares of corn within 2.0 kilometers of the trap as well as the average distance to wind blocking features on the north side of the trap. The non-spatial variables used were cumulative trap catch and date of first

silk. A dynamic simulation model was also created. This was designed to filter from the trap catch those moths coming from plantings outside of the trapped planting. This model functioned by creating map surfaces in the GIS showing for each day the relative contribution to catch for each location around the trap. This map surface was the product for each location of relative moth population levels and the likeliness that a moth positioned there would be captured by the trap. The modified cumulative trap catch was expected to correlate more strongly to damage levels than the unmodified trap catch, but no run of the model produced a significant improvement in the correlation. In the process of collecting data for this project, circumstantial evidence was obtained which indicated that high synchrony between valley-wide moth catch levels and valley-wide timings of silking in corn could be used as an indicator of high damage years.

Use of a Geographical Information System to Modify Pheromone Trap-Based  
Predictions of *Helicoverpa zea* (Boddie) Damage.

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## **Use of a Geographical Information System to Modify Pheromone Trap-Based Predictions of *Helicoverpa zea* (Boddie) Damage**

### **1. INTRODUCTION**

The Corn Earworm (*Helicoverpa zea* Boddie) is an important crop pest in the United States. It shares with other members of the genera *Heliothis* and *Helicoverpa* four traits: 1) polyphagy, 2) high mobility, 3) the ability to enter into a facultative diapause, and 4) high fecundity (Fitt, 1989). These traits cause these insects to be important crop pests worldwide.

The corn earworm has a wide host range. A search through the literature resulted in a total of 42 crop hosts attacked, as well as 33 genera of weed hosts (Isely, 1935; Barber, 1937; Neunzig, 1963; Graham & Robertson, 1970; Sparks et al. 1971; Roach, 1975a; Gross & Young, 1977; Stadelbacher, 1980; Stadelbacher, 1981; Mueller & Phillups, 1983; Stadelbacher et al. 1984; Harris & Phillups, 1983; and Pearson et al., 1989). Though known to attack many crop hosts, the common crop hosts are corn, alfalfa, tomato, soybeans, and cotton. Of these, corn is preferred (Johnson et al., 1975). Because of its wide range of crop hosts, the corn earworm is known by several common names including the cotton bollworm and the tomato fruitworm.

The earworm has the capacity to migrate long distances. Because of this, earworm populations commonly infest corn in areas as far north as Southern Canada (Hardwick, 1965) even though it is not capable of surviving the winters of most areas north of the 45° latitude (Snow & Copeland, 1971). Hartstack et al. (1982) observed captures of earworm moths in College Station, Texas 19 days before emergence of over wintering pupae from diapause. They believed that these moths originated in Mexico. Similarly, Stadelbacher and Pfrimmer (1972) observed moth captures in light traps a month and more before the first capture of moths from emergence cages. Raulston et al. (1986) noted that south to north wind flow patterns are common in the spring for regions of Texas and Mexico close to the Gulf Coast.

Using trajectory analysis, they showed a potential for movements from 150 km over a three day period to 200 km over a five hour period. These migrating moths commonly fly at heights of 300 meters and higher (Callahan et al., 1972). Haile et al. (1975), using mark and recapture methods were able to retrieve earworm moths released on the island of St. Croix in the Caribbean from the island of Vieques 68 kilometers away. Using pollen observed on adult male *Helicoverpa zea* males collected in Arkansas Hendrix et al. (1987) were able to show that they must have come from locations at least 750 km away.

The earworm survives the winter as a diapausing pupa several centimeters below the surface of the soil. Generally, their survival rates are in the range of 5% or less in the continental United States (Stadelbacher & Pfrimmer, 1972; Slosser et al., 1975). However, winter survival in Southern Texas may reach 25% (Rummel et al., 1986). The pupae break diapause in the spring and moths begin to emerge. After mating, eggs are laid singly on whatever host is locally available. From 500 to 3,000 eggs are laid per female. Oviposition occurs most on silking corn (Johnson et al., 1975). Here, ovipositional preference is for the silks followed by leaves, tassels, stalks, and ear husks (McColloch, 1920; Ditman & Cory, 1931; Phillips & Barber, 1933; Nishida & Napompeth, 1974; Gross, 1986). Depending on temperature, the egg stage will last from 2 to 12 days (Luckmann, 1963). Emerging caterpillars feed on the host as they go through six instars. Depending on temperature, the larval period lasts from 10 to 51 days (Butler, 1976). Once the 6th instar is complete, the caterpillar drops to the ground, digs a hole, and pupates within the hole to emerge as a moth in approximately 18 days (Ditman & Cory, 1931). The number of generations per year depends on the warmth and the length of the growing season. Based upon observations of rates of development of lab and field cultures we estimated that two to three generations per year occur in the Willamette Valley of Oregon .

With each new flight, the females can oviposit on the previous host or move to another. Populations may increase in one crop without reaching damaging levels, but move later into another crop resulting in damage (Johnson et al., 1975; Kennedy & Margolies, 1985). In temperate climes, earworms are apparently cued to diapause for winter by corn maturation, lowered temperatures, and decreasing daylight (Phillups & Newsom, 1966; Meola & Gray, 1984; Lopez, 1986).

Mating and oviposition take place in the evening. Callahan (1958) determined that the degree of activity was more strongly determined by darkness

than by any internal clock. Hsiao (1978) found that at cool temperatures (10-15° C) activity was greatest in the first six hours following nightfall and that there was a burst of activity before dawn. The post-nightfall activity period was extended beyond the initial six hour period when temperatures were warmer.

On corn, the earworm feeds most heavily on the kernels within the ear. In Oregon, economic damage usually results only from ear feeding, though in some locations in Eastern Oregon heavy tassel feeding occasionally interferes with pollination. For fresh market corn, ear damage reduces the marketability of the crop. For canned and frozen corn, there are standards for allowable quantities of insect parts per quantity of product. These are set by the United States Food and Drug Administration. In addition, there are five US grades to which any corn product is assigned. These grades are in part determined by levels of insect damage. For feed corn there is evidence that earworm larvae are involved in the inoculation of corn ears by *Aspergillus flavus*, which produces aflatoxin (Fennell et al., 1975; Widstrom et al. , 1976).

### Problem Particular to Oregon

Corn is a major crop in the state of Oregon. In terms of gross dollar sales, corn crops in Oregon in 1991 were valued at \$45,394,000 (Miles, 1992). This comes to 1.8% of dollar sales for all commodities in the state. Seventy six percent of the gross dollar sales in corn came from processed sweet corn. In 1991, 399,950 tons of sweet corn for processing were produced in Oregon (Anon., 1992). This constituted 12% of the United States production for that year. Seventy eight percent of the Oregon sweet corn production came from the Willamette Valley. Other major corn growing regions within the state include the Treasure Valley region around the town of Ontario and the Columbia Basin region around the towns of Hermiston and Pendleton.

Earworm population levels and cropping practices for each of the corn growing regions within the state are different from the other regions. The types of management decisions which must be made also differ. East of the Cascades, earworm populations are considerably higher than they are to the west. Though feed corn is left unsprayed, pesticide applications are common for all corn types grown for human consumption. For these corn-types, multiple pesticide applications are

often made. The first application occurs at or just before silking. Subsequent sprays occur at three to five day intervals afterwards. Earworm feeding damage in most years can be found at any location on the ear.

Earworm populations are generally low in the Willamette Valley. Ear damage is usually limited to the tip of the ear, with older earworm larvae tending to feed farther down the ear. This latter damage is intolerable to many fresh market sweet corn growers and pesticides are applied regularly. Growers of corn destined to be processed seldom spray. This is because the canneries routinely remove the tips of the ears whether or not earworm damage is present. Therefore earworm damage to processed corn is only a problem in years when earworm populations are considerably greater than normal. Most canneries have sampling procedures to assess damage and dock growers accordingly. A typical ear damage sampling method is to remove a 50 lb. sack of corn from each truckload, inspect each ear for damage (including bird, earworm, harvest damage, etc.), remove the portion of the tip damaged by birds or earworms, and assess damage as the proportion by weight of cut tips to that of remaining ears.

The corn earworm research project was initiated at Oregon State University by our research team (Coop, Croft, Fisher, and Drapek) as the result of severe earworm damage in 1985. The purpose of this project was to provide growers and cannery field representatives with the ability to predict damaging populations of earworm. For practical management decisions this information must be available by the time corn is silking. As mentioned above, earworm moths prefer to oviposit in the corn silk. According to Ditman and Cory (1931), larvae hatching in silk took between 1/2 and 2 1/2 hours to enter the ear. It is this brief period between egg hatch and ear entry that the caterpillars are most vulnerable to both pesticide applications and biological control agents.

At the time this thesis project was initiated several earworm studies had already been undertaken by our research team. For example, four years of data on male moth flight phenologies had been collected. From these data we discovered that a major moth flight occurs every year starting from the first or second week of August. In July, moth flight levels are low. Prior to 1989 the standard trap used was the Scentry "Heliothis" trap. These traps were placed in the field in early July and would catch no moths until mid-July when a few moths would be caught sporadically until the August flight. In 1988, we switched to wire mesh Texas traps, which were much more efficient at catching moths (Drapek et al., 1990). The traps

placed in early July immediately started catching an average of two to three moths per trap day. Apparently moth flights began earlier than we had realized. In 1989, Texas traps in place by early May began catching moths on May 22. A flight peak occurred during the first couple of weeks of June which was almost as high as the August peak. In all years, the August flight peaked around the last week of August or the first week of September and then rapidly dropped off towards the end of September. In one year when traps were left in some fields post harvest, a few moths were even caught as late as November.

At the start of the earworm research effort it was hoped that pheromone catch could be used to predict damage levels, but subsequent research showed the correlation between trap catch and damage level to be weak. The moth catch value used in these studies was the cumulative moth catch from the first appearance of tassels emerging from leaf whorls to the first sign of silking. The correlation between trap catch and damage could be improved by lengthening the period for which cumulative catch was determined. For example, cumulative trap catch from first tassel to 50% silk was more highly correlated with damage. However, any model using these lengthened catch periods would provide damage predictions too late for effective control measures.

Clearly, additional information was needed to predict damage. As can be seen in Figure 1, there also is a relationship between date of first silk and subsequent damage. When these two variables are combined in a multiple regression model they produce a model with an  $R^2$  of 0.641 (Table 1; Coop et al., 1992). Though this model produced a lower  $R^2$  than was obtained by Chowdhury et al. (1987), it was purposefully restricted to presilking trap catch.

Coop et al.'s regression model has been used as input to an earworm pest management simulation computer program, CEWSIM (Coop et al., 1993). CEWSIM was designed to be a decision support program that predicts pest infestation levels and economic loss for growers and cannery field representatives. The regression model results provide the basic prediction of percent infestation. Temperature driven earworm and corn phenology models provided a prediction for the distribution of earworm age classes at the time of harvest. These are used to produce a relative distribution of damage lengths down the ear which, when placed on top of the predicted percent infestation levels can produce a predicted distribution of ear damage lengths. From this an estimate of economic loss per hectare due to earworm can be calculated knowing the value of crop per hectare, average ear

weights, average weights of different lengths of tip portions cut off the ears, and simulating the cannery dockage method described above.

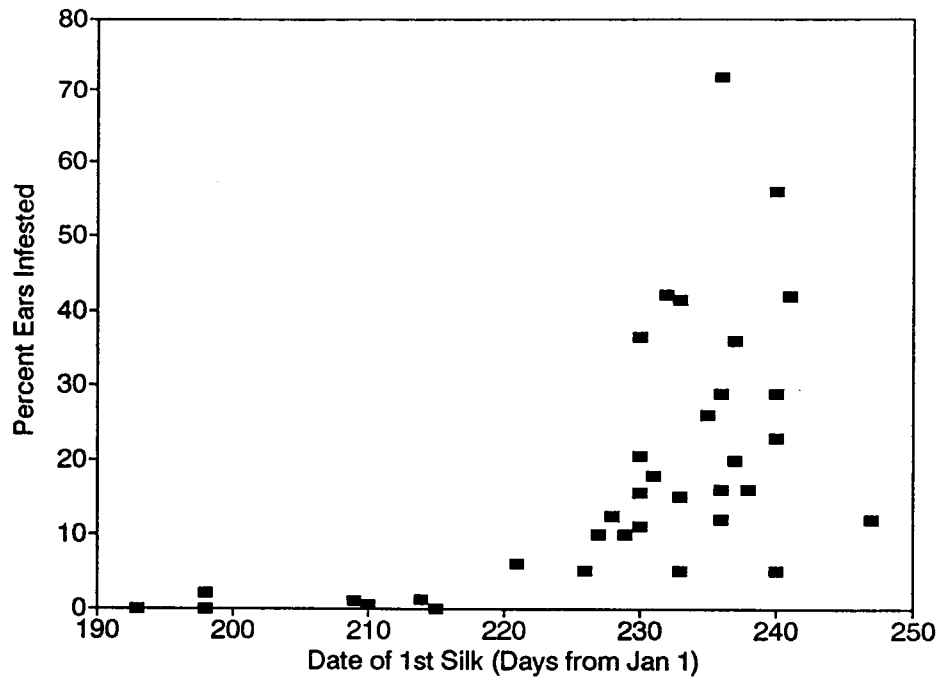


Figure 1. Scatterplot of Date of 1st silk (given in terms of days since Jan. 1) vs. percent ears infested. Each dot represents observations from one site. Data was collected in 1987 and 1988.

A problem with the damage regression model described above is that it only considers conditions within the planting (silk date, trap catch); no information outside of the planting is taken into account. Three particular external features that might impact pheromone trap based damage predictions are: 1) positions of corn plantings around the trap, 2) timings of corn plantings around the trap, and 3) positions of wind blocking features.

Table 1. Two variable regression model relating pheromone trap catch and date of first silk to subsequent damage levels.  $y = \sin^{-1}(\sqrt{\text{prop. infested ears}})$ .  $x_1$  = Date first silk observed (days after 31 May).  $x_2$  = cumulative moths captured in the pheromone trap from first tassel to first silk ( $\sqrt{X \pm 0.05}$  transformed). Degrees of freedom = 52.  $R^2=0.641$ . Taken from Coop et al., 1992.

Independent variable	Regression Coefficient	SE	t value	P
Intercept	-18.320	6.860	-2.67	0.010
$x_1$	0.427	0.0100	4.28	0.000
$x_2$	1.394	0.313	4.45	0.000

There are two major ways in which timing and position of corn plantings can affect pheromone trap catches. These are: 1) affects on regional earworm population levels and 2) affects on local moth-trap dynamics. Conceivably, high concentrations of corn at attractive stages of growth during moth migration periods could raise regional moth populations. These increased populations could cause nearby plantings to also sustain high damage levels even though they may not have been at a particularly attractive stage at the time of moth migrations. Local moth-trap dynamics depend on where the trap is placed and consequently across what type of terrain the pheromone plume is traveling. A plume traveling within easy flying distance of high moth concentrations will draw in more moths than would be expected from a plume traveling through locations remote to moths. For this reason the moth catch from a trap placed in a small isolated planting should be interpreted differently from that of a trap placed in an area with large contiguous areas of corn.

Wind blocking features are features which interfere with normal wind flow around the trap or potentially act as blocks to pheromone plumes traveling downwind of the trap. As this definition implies, these features are seen to affect trap catch by affecting moth-trap dynamics. These features include objects such as tree rows, wooded areas, large abrupt hills, or large buildings close to the trap.

In summary, the hypothesis to be tested in this project was that information on positions and timings of corn plantings as well as positions of wind blocking features could be used to improve pheromone trap based predictions of earworm damage in sweet corn.

## 2. LITERATURE REVIEW

### Determining Earworm Population Levels and Predicting Damage

Allen et al. (1972) distinguish between two goals toward which insect sampling is directed in integrated pest management: decision making and population estimation. Decision making sampling is directed towards determining if pest population levels are great enough to warrant control actions. This is the type of sampling that farmers and IPM consultants are interested in. Population estimation sampling is directed towards establishing population trends and is of most use to researchers. Though any sampling done for one of these goals will also provide information relevant to the other, the optimal sampling methods for these goals are likely to differ from each other. This section of the thesis will concentrate on methods used to sample *Helicoverpa zea* with the goal of making control decisions, but will also refer to other sampling studies when they provide relevant information. I will consider all life stages of the corn earworm for their potential usefulness in decision oriented sampling.

Because it is the late instar larvae of the earworm that causes most of the economic damage, the sampling of earworm larvae seems a likely candidate for decision oriented sampling. Indeed, larval sampling is commonly done in several crops that are attacked by *Helicoverpa zea*. Larval sampling in these crops is done by shake cloth, sweep net, beat buckets, shake buckets, and by mechanical vacuum collection devices (Nilakhe and Chalfant, 1982; Ellington et al., 1984; Linker et al., 1984; Steward et al., 1991; Studebaker et al., 1991). These sampling methods have high correlation with absolute measures of population levels. Crops for which these sampling methods have been used include peanuts (Linker et al., 1984), cowpeas (Nilakhe and Chalfant, 1982), cotton (Pyke et al., 1980; Ellington et al., 1984), grain sorghum (Steward et al., 1991), and soybean (Studebaker et al., 1991).

For sweet corn, there are two major problems with monitoring larvae: 1) larvae are hidden in the ears and therefore are difficult to sample, 2) the information gained by a larval survey arrives too late to allow for effective control measures. The larval sampling methods used on other crops were based on knocking off exposed larvae on leaf surfaces. One exception to this rule was a sequential sampling method developed by Allen et al. (1972), which called for examinations of terminals



and fruiting bodies of cotton plants. In corn the larvae are buried beneath the husks and no amount of knocking or shaking will remove them. Therefore to sample for earworm larvae in corn, ears must be opened one at a time and examined. This is a time consuming process. Also, because earworm larvae are buried under the husks they are immune to chemical and most biological control measures. As mentioned in the introduction, chemical control measures are directed against 1st instar caterpillars emerging from the eggs in the silks. Therefore any sampling method needs to occur before egg hatch.

Sampling for the presence of eggs could be timely. It has been recommended as a pest management tool for both tomatoes (Zalom et al., 1990; Hoffman et al.; 1991a) and sweet corn (Scott et al., 1984; Fisher & DeGomez, 1984). Egg sampling in sweet corn is recommended as a second step for earworm monitoring by extension publications from both the University of Idaho and Oregon State University. For Idaho, egg sampling is recommended for fields which silk after 1,300 growing degree days (Max. Threshold=95° F, Min. Threshold=55°F). The Oregon publication recommends egg sampling when Scentry vinyl "heliiothis" pheromone traps armed with Trece lures capture 30 moths a week during silking. Zalom et al. (1990) and Hoffman et al. (1991a) describe egg sampling schemes for tomatoes. Hoffman's method is a sequential sampling scheme which also takes into account egg parasitism in its determination of economic population levels.

Though egg sampling does provide the most direct estimate of earworm population levels at the stage where control measures are likely to be effective, it does have several drawbacks. First, egg sampling is work intensive and difficult. Early in this earworm research effort we attempted to sample corn silk for eggs. Despite spending considerable time in several fields, we were able to find none. Nevertheless, moderate to high damage levels were subsequently observed in these plantings. We were maintaining a laboratory earworm population at the time and had an adequate "search image" for earworm eggs. The sampling difficulty would only have been worse for someone with little or no exposure to live earworm eggs.

A second problem with egg sampling comes from relating egg population levels to subsequent larval populations. Even though egg sampling provides a population estimate at the best time for control measures, a high population of eggs does not necessarily mean that high earworm damage levels will subsequently be observed. Terry et al. (1989) developed a sequential sampling method for *Helicoverpa zea* eggs in soybean. Though they felt that their method would produce

a reasonably accurate estimate of the size of the egg population, they did not consider this method to be appropriate in a pest management context. They questioned the trustworthiness of an egg sample to predict population levels of late instar larvae. They noted that the predation on and establishment success rates of *H. zea* larvae were quite variable. It should be noted that except for larval stages, which we have already established are not suitable for sampling, the sampling of any life stage will have this source of error.

The monitoring of adult earworms generally is done with some kind of trap. Other monitoring methods, such as the sugarline sampling method described by Chowdhury et al. (1987), have only been used in research efforts directed towards the improvement of understanding trap/moth interactions. The trapping of adults is easier than egg sampling, but is further removed biologically from the late instar larvae. With adult sampling, in addition to error coming from variances in larval mortality, there is variable egg mortality and ovipositional activity. Because of these additional sources of error, the use of traps versus egg sampling represents a trade-off between ease of use versus relative accuracy.

Light traps seem to have been the principle moth trapping method prior to the invention of the "Texas" pheromone trap (Hartstack et al., 1979) and the determination of the chemical components of the pheromone (Klun et al., 1979), which opened the path to the synthesis of artificial lures. Light traps do have several advantages over pheromone traps. In comparing catches of moths in black light traps versus pheromone traps Hendricks et al. (1973) and Roach (1975b) found that *Helicoverpa zea* was strongly attracted to black light traps. In both studies, pheromone traps were observed to catch numbers of moths comparable to black light traps during periods of low populations but considerably less when population levels were high. The authors of these studies attributed the negative relationship between relative pheromone trap catch and moth population to competition with feral calling females. It should be noted that the pheromone trap used in both studies consisted of a caged female moth between two flat plates, one of which had a sticky surface. In later years, traps using such sticky surfaces to retain moths have been shown to catch considerably fewer moths than the Texas trap (Drapek et al., 1990; Gauthier et al., 1991). In addition, Roach mentions that because of difficulties in maintaining a proper stock of female moths, they had to be kept in the trap beyond their peak calling periods. When Texas Traps armed with synthetic lure were compared against 40 Watt black light traps, the pheromone traps were found to catch twenty times as

many moths at College Station, Texas during the months of April and May when moth populations were very low (Hartstack et al., 1982). The authors of this study concluded that: "This sensitive trap-lure combination has enabled the detection of moth populations in the spring that previously went undetected or were thought to be of insignificant numbers."

An advantage that light traps have over pheromone traps is that they will capture both females and males. Roach (1975b) observed nearly equal catches of males and females in light traps; Hendricks et al. (1973) observed catches of 66.1% males. Since oviposition is done by females, it would seem logical to expect that catches of females would provide more direct information on oviposition activity. However Lopez et al. (1979) observed a higher correlation between male moth catch in light traps versus oviposition than they did for females. They attributed this phenomenon to a probable loss of attractiveness of black lights to ovipositing females.

Compared to pheromone traps, light traps have relatively few potentially confounding external factors. Temperature and precipitation probably will affect light trap levels. Nemec and Chalfant (1982) and Lopez et al. (1979) observed peaks and valleys in light catch levels which corresponded to phases of the moon. Peak catches occurred at new moons and reduced catches occurred at full moons. They also observed that oviposition levels experienced the same peaks and valleys and concluded that the light traps were correctly recording changes in moth activity levels.

Research and use of pheromone traps have come to predominate over light traps. A search through the AGRICOLA database of research publications shows a change in research emphasis from light trapping in the 1970's to pheromone trapping after 1980 (Figure 2). The main reason for this shift of emphasis is probably the relative ease of use for pheromone traps. From our experience in Oregon we came to see the advantages of pheromone traps. In the beginning of our research effort we investigated using light traps. The traps we used were the standard 15 Watt vertical fluorescent lights surrounded by 4 vertical metal baffles and placed over a funnel which pointed into a capture chamber containing Vapona strips. These traps proved difficult to maintain in the field. One trap ran on alternating current and required the presence of some standard power source. Another ran on rechargeable 12 volt car batteries. Two car batteries were alternated once every other day. One would recharge while the other operated the trap. In

contrast to results reported by Hendricks et al. (1973) and Roach (1975b), very few earworm moths were ever captured by these traps. Large numbers of other insects (mostly microlepidoptera) were caught and these specimens had to be sifted through in order to find the occasional earworm moth. At peak periods, two earworm moths would be captured per night, but on most nights nothing would be captured (unpublished data).

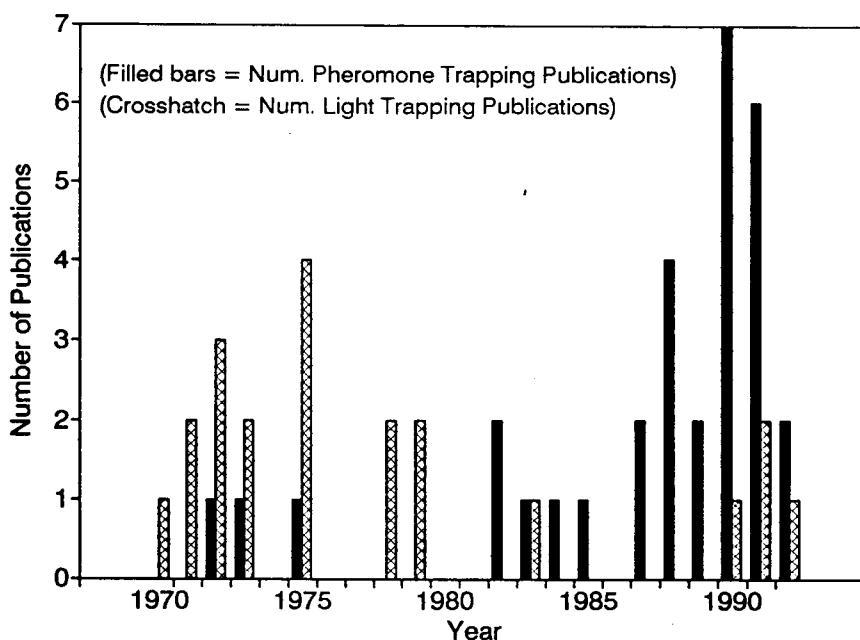


Figure 2. Numbers of publications found as a result of searching through the AGRICOLA database of monographs and serials received at the National Agricultural Library. The database was accessed using SilverPlatter (v. 3.11) CD-ROMs. The search used was: "FIND (heliiothis zea OR helicoverpa zea) AND (pheromone trap(s) OR black light trap(s) OR light trap(s))". Numbers listed are numbers of publications for each year with the above mentioned word combinations either in the title or in the descriptor list.

Many pheromone traps have been tested for monitoring earworm moths, but the wire mesh cone trap designed by Hartstack et al. (1979) is currently the most commonly used (Hartstack et al., 1982; Slosser et al., 1987; Leonard et al., 1989;

Drapek et al., 1990; Witz et al., 1990; Gauthier et al., 1991; Hoffman et al., 1991b; Latheef et al., 1991; Weber and Ferro, 1991; Coop et al. 1992). In our own experience, it proved superior to the Trece 1C, Scentry "heliiothis", pan, and Hara traps (Drapek et al., 1990).

Despite their relative ease of use, pheromone traps have some problems associated with them. Though they are more specific than light traps, pheromone traps will catch non-target moths (Weber and Ferro, 1991). Earworm pheromone traps in the Willamette Valley often capture *Heliothis phloxiphaga* moths as well as moths of the genus *Leucania* (Unpublished data). Loss of wing scales can make the differentiation of these species difficult. Because of this, trap inspectors need to be aware of these other moth species and know how to identify them.

The biggest problem with pheromone traps is that they are difficult to interpret. Stinner et al. (1983) argue that if pheromone traps are to be used to predict damage, they should be able to determine actual population densities. This position is also taken up by Gauthier et al. (1991) who state: "Until we better understand the relationship between corn earworm trap catch and field density, growers and agricultural advisors must be conservative in using pheromone traps." Riedl and Croft (1974) envisioned the interpretation of traps to predict damage as a three phase process: phase I) Determining population levels based on trap catch, phase II) Determining subsequent levels of damaging immatures, and phase III) Carrying the phase 2 level analysis over multiple generations. Processes which Riedl and Croft envisioned as complicating phase 1 include: a) the density of moths; b) the length of the trapping period; c) male moth activity levels, d) trap efficiency; e) age class distribution of males and how different ages respond to pheromones; f) effects of micro climate on pheromone dispersion; g) type and age of pheromone capsule; h) trap design, size, and shape; i) age and condition of trap; j) number of moth producing host plants within range of the trap; indigenous moth population versus immigrants from outlying areas. Understanding phase II is a life table analysis problem. Because earworm pheromone trapping in sweet corn is directed towards making predictions within a single generation Phase III does not come into consideration.

Latheef et al. (1991) studied the relationship between trap catch and oviposition for corn earworm in commercial corn fields and found a weak nonlinear relationship. Conducting a cross correlation analysis on the data they found that on average the  $R^2$  between trap catch and oviposition was maximized when a two day

time lag was added to trap data. However, this time lag was not absolutely consistent from location to location or from year to year. Factors they list as possibly having affected the trap catch/oviposition relationship include temperature, moth age, pheromone release rate, moonlight, crop phenology, crop cover, and competition between calling females and the trap.

Attempts to use pheromone traps to determine corn earworm populations and predict damage have had mixed results. As mentioned in the introduction, studies by Coop et al. (1992) and Chowdhury et al. (1987) resulted in multiple regression equations which produce earworm infestation levels in corn as output and include pheromone trap catch as one of several input variables. Chowdhury's model produced a stronger fit, but required late season information which made it impractical for pest management purposes. Coop's model was more compatible with pest management needs and had a reasonably strong fit to the data upon which the model was built; however it had a higher error variance than would be desirable. An additional study of this nature conducted in sweet corn was done by Wiesenborn and Trumble (1988). They conducted a stepwise regression analysis with *Helicoverpa zea* egg density in sweet corn as the output variable and the following list of potential input variables: field size, adult pheromone trap catch, crop maturity, hectares of older corn nearby, distance to the closest older corn, and the mean distance to older corn. Of these input variables they only found field maturity and the distance to the closest older corn field to be significantly correlated to egg density. Pheromone trap catch was not significant, though they noted that the correlation between trap catch and egg density could be increased if a nine day delay was added to trap catch.

In cotton, several researchers have shown a limited correlation between pheromone trap catch and oviposition. Leonard et al. (1989) combined the pheromone trap catches for *Helicoverpa zea* and *Heliothis virescens* and found moderately strong correlations with oviposition through June and July over three years. If the entire season over which oviposition takes place (June - September) was considered, they found low correlations. They discussed two hypotheses explaining the loss of correlation during the second half of the season: 1) higher late season populations of moths resulted in increased competition with feral calling females, and 2) the decline of flowering cotton somehow altered moth response to the pheromone. Witz et al. (1990) looked at how trap catch and oviposition correlated in cotton over time delays of -9 to +15 days. They found that trap catch could

correlate significantly with oviposition, but that plotting correlation's versus delays resulted in more than one peak. It was difficult to tell which peak corresponded to the "true" relationship. Peak correlations were close to 0.8. These authors concluded that pheromone traps had potential as population indicators, but that greater understanding of the dynamics involved was needed.

### Use of Models in Earworm Pest Management

As noted in Croft & Welch (1983) and in Tummala & Haynes (1977) there often is a trade-off between monitoring and modeling in insect pest management systems. Early in the development of any systematic approach to pest management, considerable effort must be expended in monitoring the insect pests being managed. As more information becomes available, models can be developed and improved upon. Often the amount of monitoring activity can decrease as models improve. In this section I will look at the impacts of modeling efforts on earworm management.

There are many different kinds of modeling efforts which have been used in earworm research. The multiple regression equations described above for interpreting pheromone trap results are models. These were empirical models intended only to describe as a function the relationship between one output variable and one or more input variables. Other such single-function modeling efforts in earworm research have included the development of functions to determine development times for different life stages of earworm and functions describing the initiation, duration, and termination of diapause for pupae living in the soil during winter months. These single function models are often used as building blocks to systems models. Systems models represent the dynamic interactions of multiple processes. These models are often represented as flow charts with inputs and output to any process flowing in and out of other processes. Several such systems models have been developed for earworm management. These types of models simulate the behavior of many biological components of the agricultural system as they affect each other and are affected by abiotic-physical constraints. In this section, I will look at some of the single function modeling efforts that have taken place, some of the systems models which have been built, and some of the uses to which these systems models have been put.

A considerable effort has gone towards developing temperature driven models describing rates of development for different stages of the earworm. Early efforts in this area were directed towards fitting parameters to simple linear degree day development models (Luckmann, 1963; Mangat & Apple, 1966). These studies were conducted in the laboratory and were developed by exposing different groups of individuals to different constant temperatures and noting the amount of time required for development. Luckmann (1963) studied egg development and determined a threshold of 54° F and a 1,844 degree-hour requirement for completion of egg development. Mangat & Apple (1966) looked at development from egg hatch to moth emergence and found a threshold temperature of 54.7° F and a 690.2 degree-day requirement.

The development models used by Luckmann and Mangat & Apple simplified reality in a couple of important ways: 1) they modeled a nonlinear process as a linear function and 2) they were deterministic models that did not consider variable development rates within a population. Stinner et al. (1974) described a more realistic nonlinear temperature driven development model. This model was fitted to development data for *Helicoverpa zea* by Butler (1976), Stinner et al. (1974a), and Butler & Scott (1976). Stinner incorporated this model in the HELSIM systems model (described in more detail below). Stinner et al. (1975) describe another model which incorporated variability in development times. This model was also incorporated into the HELSIM model. Sharpe et al (1981) looked at variable development time models for two different *H. zea* biotypes at several constant temperatures. They were able to show that a single distribution function is adequate for all temperature/biotype combinations and that a normal distribution worked well. They also noted differences between optimal models for the two biotypes.

Modeling spring emergence of moths is similar to modeling egg and larval development rates. All are temperature driven functions, though the modeling of pupal emergence in the spring is complicated by the fact that the temperatures used by the model are most appropriately soil temperatures which may vary additionally as a function of the depth of the pupa in the soil (Logan et al., 1979). Logan et al. (1979), Rummal & Hatfield (1988), and McCann et al. (1989) all published papers on temperature driven spring emergence models for *Helicoverpa zea*.

Scott (1987) published a model which is not a systems model, but does attempt to answer the kind of question that systems models are often applied towards: when can we expect an insect pest outbreak to occur? Scott was able to



demonstrate a rough ( $R^2=0.66$ ) correlation between cumulative degree days in any one year and peak earworm populations the following year in Southern Idaho. Scott attributed his ability to model earworm populations this way to the fact that the Idaho earworm population is isolated.

In 1974, Hartstack and Hollingsworth published a paper describing a systems oriented model for cotton pest management. The pests featured predominantly in this model were *Helicoverpa zea* and *Heliothis virescens*. The model was called MOTHZV and featured processes such as estimates of population levels from light trap data, degree day models to predict timing of generations, crop phenological models, migration of moths from corn into cotton, and larval cannibalism. The sub models for these processes are described more thoroughly in Hartstack et al. (1976b). The purpose of this model was to predict timings and sizes of population peaks. Through the 1970's and early 1980's, MOTHZV was available through county extension offices on a computer network (BUGNET). In the 1980's a more user-friendly shell and fleahopper models were incorporated. This modified version known as TEXTCIM was made available to run on the portable computers of individual growers (Legaspi et al., 1989). Legaspi et al. (1989) argue that the value of TEXTCIM lies in its ability to predict timings and magnitudes of economic pulses five to ten days in advance, thus giving growers time to respond appropriately.

Another major earworm management systems model was created in North Carolina for soybean management (Stinner et al., 1974b; Johnson et al., 1975). This model, called HELSIM, is similar to the MOTHZV/TEXTCIM model in that it includes an insect phenology model, a crop phenology model, oviposition, and mortality due to cannibalism. It differs from MOTHZV/TEXTCIM in that it more explicitly models oviposition as a process involving regional moth populations choosing among multiple plantings for several host crops at various stages of development and scattered in space. All crops are assumed to be in plantings of approximately constant size and randomly distributed. Moths are attracted to any planting as a function of the crop and stage as well as the square of the distance between moth and planting. For use in HELSIM, Johnson et al. measured relative attractiveness of 16 stages of corn, 14 stages of tobacco, 14 stages of cotton, and 6 stages of soybeans. Currently, a simplified version of HELSIM is available. This version is based upon the original model but uses a Leslie matrix model instead (Yu et al., 1992). The net effect of this is some loss of generality in exchange for

computer code which runs faster and requires less memory. This condensed version of the model will be easier to incorporate into decision support software.

Other models have been developed in cotton and soybeans. Whereas MOTHZV/TEXCIM and HELSIM were created initially as insect pest oriented models, other systems models have been developed as additions to detailed physiological crop models. Szemedra et al. (1990) developed a soybean pest management model off of the Soybean Integrated Crop Management Simulation Model (SICM) and Thomas (1989) created a sub model (HELDMG) to be incorporated with the GOSSYM/COMAX cotton model. Thomas takes advantage of the fact that GOSSYM models explicitly the patterns of cotton boll and square development on cotton plants. HELDMG considers the fact that: 1) each instar of *Helicoverpa zea* and *Heliothis virescens* caterpillars has different preferences for different ages and positions of cotton bolls and squares, and 2) fruit positioned at different places on the cotton plant have different chances of senescing and dropping off before harvest. HELDMG, therefore looks at within-plant spatial patterns of fruiting and insect feeding and from this adjusts the economic threshold.

Coop et al. (1993) developed a systems model for managing corn earworm in processed sweet corn fields. This model included predictions of earworm infestation levels based on pheromone trap catch and produces damage distributions in corn ears based on earworm development models, historical weather data, and measured mean damage lengths per larval stage. The model conducts two simultaneous runs: one with and one without pesticide applications. Differences in damage levels between the two runs are used to produce a net benefit of the pesticide application. This program was written to run on personal computers and is available to growers, extension agents, consultants, and cannery field representatives.

Systems models of the earworm crop agricultural ecosystems have been used to answer a wide variety of questions. A common use is the prediction of numbers and timings of peak population levels. Slosser (1980) suggests using MOTHZV to predict timings of peak oviposition periods in order to time alterations in irrigation schedules and produce sub-optimal micro habitats for oviposition, egg hatch, and early larval development. Systems models can be used to come up with economic thresholds for pests which consider more than just pest counts. These economic thresholds can include information on: other pertinent field conditions (e.g. counts of beneficial insects), changing costs, changing expected revenue, considerations of risk and the growers degree of risk aversion, and considerations of less easily

quantified costs (such as the chance of developing pesticide resistance). By simulating the affects of predators on *Heliothis/Helicoverpa* populations, Hartstack et al. (1976c) came up with a modified control threshold which considers both pest egg counts and predator counts.

Systems models also allow for the investigation of alternative management strategies. For example Kennedy et al. (1987) compared two types of corn resistance, antixenosis versus antibiosis, to see what effect they have in multi-crop systems. As expected, antixenosis (reduced attractiveness for oviposition) resulted in increased earworm populations in alternative hosts. Unexpectedly, antixenosis also resulted in increased earworm populations in corn. This was because the earworms that would have laid their eggs on corn normally now oviposited in alternative crops which did not have the same levels of larval cannibalism as does corn. More caterpillars survived to the next generation to reinfest corn. Using the earworm/soybean system and a systems modeling approach Szmedra et al. (1990) compared three kinds of pest management choices: 1) strict adherence to recommended economic thresholds, 2) a loose adherence to the economic thresholds, and 3) calendar sprays. They were able to show that though the use of economic thresholds resulted in the highest economic return on the average, there was a wider variation of economic return for these methods. A risk-averse farmer would actually be better off following calendar sprays. They conclude that if economic thresholds are to be used more in the future they should be designed to consider stochastic field conditions and the farmer's level of risk aversion.

### Regional Landscape Features and Pest Management

Prior to the 1970's, pest management systems analysis and modeling efforts were on a site-by-site basis and did not take into consideration spatial and temporal patterns of host and non-host plantings. Starting in the late 1970's researchers began to argue for the importance of pest management from a wide-area view (Rabb, 1978) and began to take particular notice on how planting patterns of both hosts and non-hosts could affect population dynamics (Stinner, 1979). Rabb noted that too often pest management was directed towards temporary suppressive control recommendations such as economic thresholds, but that long-term control could be obtained from fundamental redesigns of cropping practices. He suggested that

entomologists work towards developing recommendations on crops and varieties to plant, locations to plant, rotations to follow, as well as planting dates. As stated by Rabb: "Crop mix and cropping practices determine in large measure the quantity, quality, and seasonal availability of food, space, and associated organisms as well as influencing micro climate." Kennedy and Margolies (1985) noted how polyphagous mobile arthropod pests could move from crop to crop through the season as different host crops were planted and reached maturity. They discussed also how early season host crops can function in two different ways; either as trap crops that draw pest arthropods in for subsequent destruction or as "nursery" crops that provide a place for pest populations to build up.

With the new-found interest in spatial and area-wide characteristics of cropping system came a new-found interest in developing new sampling methods to suit the larger study scales. Remote sensing techniques now have become important as means of characterizing landscape patterns (Wiley, 1989). Remote sensing techniques used include photography, videography, multispectral imaging, thermal imaging, radar, acoustic sounding, and low-light optical methods. Platforms from which these methods can be applied include ground level, aircraft, and satellites. As an alternative to these remote sensing methods, Witz et al., (1986) examined sampling crops with grid networks and then using computer contouring methods as a means of determining cropping patterns over a wide-area. With sample points located 3.2 kilometers apart from each other, they were able to provide adequate maps of land usage's for features taking up more than 7% of the study land area.

Spatially referenced data require the use of different analytical and data management tools than are used for non-spatial data. Liebhold et al. (1993) review the use of geographical information systems (GIS). GIS's are computer systems "capable of assembling, storing, manipulating, and displaying geographically referenced information" (Liebhold et al., 1993). Within a GIS, any spatially referenced data (crop patterns, soil maps, topography, insect population levels etc.) can be stored and manipulated. Each data type is stored in a distinct map layer. GIS's allow for the analysis of interactions within and between these map layers. Within the field of entomology, GIS technology is still very new and few studies have yet been published that use it. The greatest use of GIS technology in entomology so far has been from forest and rangeland insect studies. Liebhold et al. (1993) note that this probably is because forest and rangeland systems are managed

at larger geographic scales than agricultural systems. With the advent of the concept of area-wide pest management in agriculture this could change.

There are many studies in insect movement that incorporate spatial features. To attempt to review all of these studies is beyond the scope of this thesis. Most of these studies involve simple and experimentally contrived spatial patterns. Examples of these kind of studies include: mark and recapture studies, studies of insect movement in polycultures, studies of movements of insects between pre-arranged patterns of small plantings, studies of movements of insects across a barrier, etc. Relatively few studies have involved detailed maps of complicated landscapes to study insect population behavior for specific locations and times. Such landscape based studies have not only included studies of insect movements, but have also involved predictions of insect population or plant damage levels. These kinds of studies are most appropriate for GIS technologies and are potentially the most useful for the development of wide-area pest management. The examples presented in the paragraphs below show the range of scales, the kinds of questions investigated, and analytical methods used in these studies.

Just as forest systems currently use GIS's more extensively than agricultural systems, they also have more of a history of incorporating spatial patterns in their analyses of population dynamics. A classic example of this is the simulation modeling efforts done in the 1960's and 1970's to analyze spruce budworm outbreaks (Clark et al., 1978). These studies did not involve the use of GIS's, but undoubtedly would have, had the technology been available. For these, the landscape pattern mapped was "forest density". This was a descriptive variable which was a function of tree species present and the tree age class distribution. Data inputted into this model were maps of budworm populations and forest density values, as well as data on prevailing winds. The model then proceeded to simulate population patterns over a 7,000,000 hectare forested area of New Brunswick, Canada. The basic sub-model used in this study determined budworm population density as a function of forest density. An additional sub-model of budworm migratory movement added a spatial component. An interesting outcome from this model was the observation that the use of chemical suppression methods tended to maintain the budworm at outbreak levels throughout the region of study for many years.

In agriculture, many studies have been conducted which consist of wide-area surveys of insect levels, crop locations, and crop stages through time. These studies

are most often conducted for polyphagous insects living in a heterogeneous region. The goal of these studies is to understand the insect population patterns through the season as various hosts come in and out of pest-attractive life stages. For these studies, either a gridded network or a transect line of insect traps is placed over a wide area. Trap catches and stages of nearby host plants are monitored over time. Often damage or larval samples are taken as well. What emerges from these studies is a dynamic picture of insect population movements from host to host as the season progresses. Ideas of host preferences through time can be obtained as well as a greater understanding of locations and times where pest populations are particularly vulnerable. Studies of this type have been done for various species of fruit fly (family: Tephritidae) in Hawaii (Vargas et al., 1983; Nishida et al., 1985; Harris & Lee, 1986; Harris et al., 1986; Harris & Lee, 1987; Vargas et al., 1990), field crickets (Tennis, 1983), orange tortrix (*Argyrotaenia citrana*) Knight and Croft (1987), tufted apple bud moth (*Platynota idaeusalis*) (Knight & Hull, 1988), as well as for *Helicoverpa zea* (Slosser et al., 1987).

In a gypsy moth study, Gage et al. (1990) also used a grid of traps to monitor adult insect populations over a large area. Site characteristics were also mapped so that the area around each trap could be evaluated for gypsy moth habitat quality. Though there is a resemblance in the field methods used for this study to those described in the paragraph above, the goal here was different. This time the goal was to predict gypsy moth risk levels one year in advance for all locations throughout the state. This was intended to give an indication of where control efforts should be concentrated over the next year. Risk predictions were based on trap levels for the previous two years. For locations between traps, an interpolated value was used. Output from the system was a state-wide map showing risk levels. Though data on site characteristics around each trap were collected and stored in a database, those data were not used for the 1990 publication.

Another wide area risk predicting study was conducted in New South Wales, Australia (Bryceson, 1991). Unlike the Gage study which ignored (for the time being) host information and concentrated on pest monitoring, Bryceson made no use of pest monitoring and concentrated on quality of locations as breeding habitat for locusts. Using Landsat MSS images and transforming to produce images of a vegetation index, Bryceson was able to show that locations which subsequently were observed to have high locust nymph populations ( $> 80 / \text{m}^2$ ) generally were also locations which had high vegetative growth as a result of March rains.

Another form of risk determination/damage prediction comes from studies which use multivariate methods, with statistics derived from spatial patterns being used as input parameters. These statistics are used in either a multiple regression or discriminant analysis to come up with either an equation relating damage/population levels to input statistics (multiple regression method) or a description of conditions significantly associated with high damage/populations (discriminant analysis). An example of this type of study was done with the corn earworm and has already been cited in this thesis (Wiesenborn & Trumble, 1988). In that study, a multiple regression model was used to show that earworm oviposition levels were associated with the maturity of the corn planting and distance to the closest older corn field. A discriminant analysis approach was taken for a study of regional habitat features and how they relate to cereal leaf beetle abundance (Sawyer & Haynes, 1985). Seasonal population values for both adults and eggs were analyzed in this study and landscape features considered included: acreages, perimeters, and shape indices for the studied plantings; local acreages of various overwintering habitats; as well as indices of patchiness and heterogeneity. The experiment was conducted over two years and looked at beetle populations in plantings of susceptible and resistant winter wheat varieties as well as spring oat plantings. In both years, for all three crop-types and for both beetle life stages, it was possible to identify five or fewer variables that could correctly place over 90% of the plantings into high or low insect population categories. However, no features proved to be consistent as indicators. The authors concluded that the spatial features determining beetle density levels were probably too numerous and interacted in too complex a fashion to be modeled by such a simple statistical model. As an alternative approach for determining the affects of landscape patterns on damage predictions, they suggested the use of simulation models.

#### Spatial Models of Moth / Pheromone Trap Interactions

In order to use pheromone traps to determine actual insect population levels, greater understanding of the behavioral of insects with respect to semiochemicals will be needed. Many mechanisms have been proposed to explain a male moth's ability to locate females using pheromones. I will not attempt to present a complete review of the topic since a considerable amount of research has gone into it. Instead,

I would like to focus on two attempts to step back from the detailed understanding of moth/plume interactions and consider spatial models of aggregate moth behavior for the region surrounding the trap. From this kind of model, map surfaces can be created that show the likeliness of catch for a moth given its position relative to the trap. A more complete review of detailed studies of moth/plume interactions can be found in Murlis et al. (1992).

Two plume models have been created which model average moth behavior over the entire area surrounding the pheromone trap. These are a pea moth (*Cydia nigricana*) model developed by Perry and Wall (1984) and a cabbage looper model (*Trichoplusia ni*) developed by Hartstack et al. (1976). Both models create the active space of the plume using a gaussian dispersion cross-wind and creating a value for any location around the trap of average concentration per unit time (Sutton, 1953). The active space is the area around the trap within which pheromone concentrations are high enough to elicit some response from the insect. Average concentration models such as this treat the origin of a Cartesian coordinate system to be the plume source location. Wind blows in a left to right direction so that the plume blows down the positive side of the X axis. Lateral and vertical plume spread resulting from turbulence are modeled as variance terms ( $f_y$  and  $f_z$ ). Other information needed includes the amount of material being emitted per unit time by the plume source ( $Q$ ) and the average wind speed ( $u$ ). Such models tend to create an elliptical region with one vertex positioned on the trap and the major axis positioned on the downwind line from the trap. Perry and Wall argue that because crops tend to absorb and re-release pheromones, such time averaged concentration models give an indication of the kind of instantaneous signals that insects receive in the field.

In Perry and Wall's model (1984), moths are assumed to fly upwind when within the active space. Upon reaching the upwind edge of the active space ellipse, the moths cast across wind either right or left. Moths that cast away from the plume are assumed to have lost the plume. Those that cast towards the plume move a distance determined by an exponential function before turning upwind again. Those that actually cross the major axis of the active space ellipse are assumed to have succeeded in finding the plume source. Moths outside of the active space ellipse are assumed to move randomly with the numbers entering the active space being determined by moth concentrations outside the space. Once a moth crosses the border into the active space region, it begins the behavior patterns described above.



The model produced by Hartstack et al. (1976) was even more simple and abstract. Perry and Wall's model did consider in a gross way such things such as anemotaxis and cross-wind casting. Hartstack's model reduced the system to some simple geometric questions: 1) how far away from the plume is the moth?, 2) what is the intersection area of the plume active space ellipse and the ellipse describing possible moth movement vectors?, and 3) what is the angle between the lines described by the moth and the trap versus the moth and the farthest downwind position in the plume active space? Likelihood of capture was a function of how much extra search time moths would have to locate the trap and the likelihood that the moth would actually enter into the plume active space region. Extra search time was calculated using a search time limit  $T$ , the wind speed and direction, and the moth's position relative to the trap. Depending on position relative to the active space, likelihood of capture was either calculated as a ratio of areas or a ratio of angles. When moths were either upwind or downwind of the trap, likelihood of capture was the intersection area described in geometric question 2 (above) divided by the area of moth flight space (also described in geometric question 2). For moths positioned cross-wind to the trap, the likelihood of capture was the angle described in geometric question 3 divided by  $2\pi$ .

Both of these papers attempted to relate processes most often studied at one scale to yet a larger scale. As stated by Levin (1992): "To scale from the leaf to the ecosystem to the landscape and beyond we must understand how information is transferred from fine scales to broad scales and vice versa. We must learn how to aggregate and simplify, retaining essential information without getting bogged down in unnecessary detail." Though both of these modelling efforts represented a simplification of moth/plume interactions, they were intended to retain the essential behavior of the system from the perspective of the larger, regional scale. Perry and Wall were able to show with an extensive set of field data that their model fit the actual behavior of pea moths from that scale. When producing regional agricultural models such as those needed for area-wide pest management, it is inevitable that such scaling problems will have to be addressed. Researchers are constrained by the fact that our scales of observation are "imposed on us by our perceptual capabilities, or by technological or logistical constraints" (Levin, 1992).

### Summary of Literature Review

In the introduction, I concluded that I would attempt to show that local landscape features can be used to improve pheromone trap based predictions of earworm damage in sweet corn. This review is intended to provide a basis from the literature to explain some of the methods used in this study. The first section on monitoring was intended to explain why pheromone trapping was used at all as a monitoring method as opposed to other options. From this section it could be seen that pheromone traps provide the easiest method for collecting information in a timely manner for control decisions. This section also showed that pheromone trap catches are hard to interpret and that simple moth catch/damage correlations are seldom effective. Greater understanding of moth/trap dynamics is needed. Since a modelling approach will be taken in this paper, a review of past earworm modelling efforts was also included. Since the approach taken in this study will involve the use of landscape patterns of corn plantings around the traps, a review of the use of landscape patterns in pest management is included. From this it can be seen that there is a precedence for the spatial regression approach which will be taken in this study. Additionally, this section concluded with the observation of Sawyer and Haynes (1985) that a simulation modelling approach would probably be more appropriate for the study of landscape patterns and how they affect predictions of damage levels. A simulation modelling approach will also be taken in my study as an extension of information gained from the spatial regression model. The final section of the literature review outlines two examples of regional models of aggregate moth behavior in relation to a pheromone trap. It is from the example of these models that the moth/plume interaction portion of the simulation modelling approach used in this thesis study comes.

### 3. Materials and Methods

#### Field Methods

Pheromone traps were placed in corn plantings prior to tasselling over two seasons, 1990 and 1991. These traps were checked on a three day interval and with each checking, the number of captured corn earworm moths was counted. The traps used were standard sized Texas wire cone traps (cone-75-50 of Hartstack et al. 1979). Scentry pheromone caps were used. These caps contain the following components: Z-11-Hexadecenal, Z-9-Hexadecenal, Hexane, and Tenox 4. This trap and lure combination is one of the most effective monitoring tools available (Drapek et al., 1990; Gauthier et al., 1991).

In 1990, 29 plantings were trapped and in 1991, 30 plantings were trapped. Plantings covered a region approximately 80 kilometers from north to south by 40 kilometers from east to west. Maps of field locations in 1990 and 1991 are shown in Figures 3 and 4. It would have been preferable to have placed all of the traps in plantings of the same variety since corn variety is known to influence the amount of earworm damage incurred (Story et al., 1983). Due to mis-communications with cooperators this ideal was not achieved, though most plantings were of variety "Golden Jubilee". In 1990, 20 of the plantings were of the variety "Golden Jubilee", 4 were "Vantage", 2 were "Citidel", 2 were "Crisp 'n Sweet", 1 was "Supersweet Jubilee" and 1 was an unidentified supersweet variety. In 1991, 20 plantings were "Golden Jubilee", 2 were "Crisp 'n Sweet", 2 were "Vantage", 2 were "Supersweet Jubilee", 1 was "1703", 1 was "Citidel", and 2 were unidentified.

Traps were placed, when possible, 75 meters within the corn field in locations where they were accessible. In some fields, the presence of linear or pivot overhead irrigation devices prevented the placement of the traps within the field since they would be knocked over by the irrigation device. In these cases, traps were placed as close to the edge of the field as possible. The fact that some traps were placed on the perimeters of the field instead of in the interior should not cause problems in data interpretation. Witz et al. (1992) found that at low populations of *Helicoverpa zea*, traps placed within 5 meters of the perimeter of cotton fields caught as many moths as interior traps. To these authors "low" populations meant

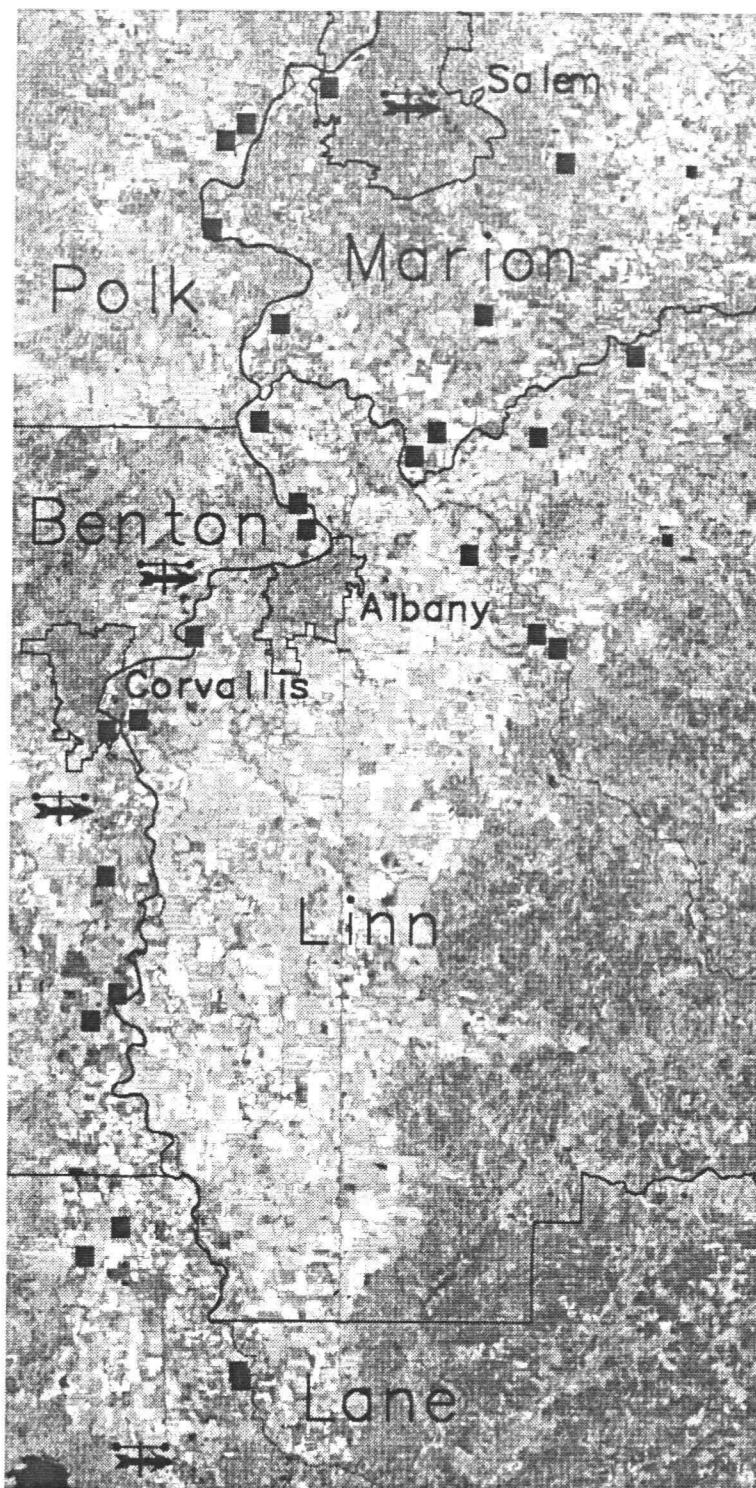


Figure 3. Locations of Plantings Monitored in 1990 Superimposed over an Image of Reflectance Values for the 3rd Spectral Band of a LANDSAT MSS image. The image was Taken August 5, 1990. Positions of wind data sites are shown by arrow symbols. Small squares mark locations that were set up for monitoring, but subsequent problems prevented their inclusion in the final analysis.



Figure 4. Locations of Plantings Monitored in 1991 Superimposed over an Image of Reflectance Values for the 3rd Spectral Band of a LANDSAT MSS image. The image was Taken August 5, 1990. Positions of wind data sites are shown by arrow symbols. Small squares mark locations that were set up for monitoring, but subsequent problems prevented their inclusion in the final analysis.

anything less than 50 moths per trap per night. Willamette Valley trap catch seldom exceed 50 moths in a night. No attempt was made to place traps on upwind sides of fields since previous testing had shown little effect of wind-side on trap catch (Drapek et al., 1990).

When traps were placed in young plantings they were set so that the base of the trap was approximately two meters off of the ground. Pheromone caps were placed at the base of the trap. Once the corn had grown to this height, the trap was raised as needed so that the pheromone cap was less than 20 centimeters above the height of the corn. Caps were changed every two weeks.

With each checking of a pheromone trap, the stage of corn development was noted. Corn development was measured in terms of number of leaves present, tassel length, percent of plants silking, and percentage of plants with brown silks. All of these measurements were taken by making observations on 20 individual plants randomly selected from the vicinity of the pheromone trap. In counting leaves on young plants, no attempt was made to distinguish cotyledons from other leaves. Tassel length on each plant was measured as the length of tassel which was visible emerging from the leaf whorl without having to pull leaves aside to view it. Corn plants with silk emerging from any of the immature ears were counted as silking. A "15% silk" meant that out of twenty observed corn plants, three had at least one ear with silks emerging. Plants were counted as brown silking if any of the silks emerging from any ear had more than 50% dried brown silk strands. A "15% brown silk" meant that 3 out of 20 observed plants had at least one ear with greater than 50% of its silks dried brown.

At some point during the field season, the area surrounding each trapped planting was mapped. For each planting, a 2.5 kilometer radius area was mapped with the center of the circle being the pheromone trap. Included in the map was the outlines of every corn planting and wind-blocking feature. Wind blocking features included large buildings within 200 meters of the trap, windrows, wooded areas, and large hills. The area within 0.5 kilometers of the trap was mapped entirely by foot. Beyond 0.5 kilometers, features were noted by driving every road within the area and visually spotting them. Corn plantings thus spotted were then mapped by foot. Wind blocking features were noted and compared with what was to be found on 1:24,000 scale USGS topographic maps.

For each mapped site, the mapping date and the stage of every planting was noted. Every feature mapped by foot was done by using a compass and pacing along

the perimeter of the feature. Features beyond 0.5 kilometers and mapped by foot were placed in context with the rest of the map by noting the distance on the car odometer from some known feature such as a road intersection to some starting point, and then taking a bearing and counting paces. The position of the pheromone trap was likewise determined so that it could be placed on a 1:24,000 scale topographic map.

Damage samples were collected so as to be as close to the harvest date as possible. When plantings were subjectively determined to be ready for harvest, a 200 ear sample was taken from every planting with a trap in it. In 1991 a 100 ear sample was taken from 49 of the non-trapped plantings within 2.5 kilometers of the trap. For trapped plantings, if corn was still unharvested 6 days after the ear sampling a second ear sample was taken. For every sampling, an effort was made to sample randomly within the planting. In 1990 sampling was done by moving in a line diagonal to the corn rows from 5 starting locations in the field: close to the trap and from each side of the field (north, south, east, and west). From each of the 5 positions 40 ears were sampled. In 1991 only the trap location was used as a starting point, but the diagonal line was extended so as to go from field edge to mid-field. For each sample the number of ears with earworm larvae or damage were counted.

In order to model pheromone plume and subsequent male moth behavior, wind speed and direction information was needed for peak moth flight hours of every day for every site. Resources were not available to collect this kind of information directly from each site, so data was obtained from weather stations operating at the Corvallis, Salem, and Eugene airports as well as data from the Hyslop Experimental Station. The Corvallis, Salem, and Eugene airports are located 6 km south of Corvallis, on the southeast side of Salem, and 10 km northwest of Eugene. The Hyslop Experimental Station is located approximately 6 km northeast of Corvallis. These sites are shown on Figures 3 and 4. The airport locations gave hourly readings of wind speed and direction, temperature, precipitation, sky cover, and ceiling height. Airport climate data was taken from approximately 10 meters off of the ground. Hyslop farm gave daily average readings of wind speed and direction as well as daily maximum and minimum temperatures. Hyslop data was taken from approximately 2 meters off the ground.

### Entering Map Data into the Geographical Information System

Final paper copies of the map were created by placing tracing paper over a 1:24,000 scale topographic map and tracing all roads, waterways, and wind blocking features within a 2.5 kilometer radius of the pheromone trap. Corn plantings were then drawn in to match up properly with these features. Though the compass and pacing method used to obtain these corn planting maps was prone to error, these errors usually could be detected and corrected to a large extent in the process of drawing these maps in the context of the more precise USGS maps.

These paper maps were digitized on the computer using the digitize program from version 3.2 of IDRISI and a Summagraphics M2201 series digitizing tablet. IDRISI is a raster-based geographical information system designed to run in the DOS environment on personal computers. All sites were digitized into a generic map location with coordinates ranging from 0 to 5000 meters in both the east-west direction as well as the north-south direction. Spatial resolution was set at one meter. The numeric attribute assigned to each planting was the degree days accumulated at that planting as of August 5 (see section below on modeling plant phenology for more details on degree day accumulation). A program was written to convert the ascii files for these maps into proper format for input into GRASS 4.0 using the program v.in.ascii. These were then converted into raster files using r.in.vect. Within GRASS, all site maps were stored in a projectionless, generic x,y coordinate location with 500 X 500 rows and columns and a spatial resolution of 10 meters. Therefore, each cell in the GRASS image represented a 100 m<sup>2</sup> square. Print-outs of all site maps for 1990 and 1991 can be found in Appendix A.

### Methods of Analysis

Two methods of analysis were conducted for this study: an empirical regression approach and a simulation approach. These two approaches are described below.



### Regression Model

The regression model was essentially a continuation of the multiple regression approach described by Coop et al. (1992) except that some independent variables of a spatial nature were added to the model. A stepwise regression approach was used with the following list of independent variables considered for inclusion into the model: 1) cumulative trap catch from first tassel to first silk; 2) date of first silk; 3-5) average distance to wind blocking features north of the trap, south of the trap, and all around the trap; 6-10) hectares of corn older than the trapped planting within 0.5, 1.0, 1.5, 2.0, and 2.5 km of the trap; 11-15) hectares of corn the same age as the trapped planting within 0.5, 1.0, 1.5, 2.0, and 2.5 km of the trap; and 16-20) hectares of all corn plantings within 0.5, 1.0, 1.5, 2.0, and 2.5 km of the trap. This comes to a total of 20 variables considered for inclusion into the model.

Average distances to wind blocking features were calculated by hand on the paper maps. Only a 0.5 km radius around the trap was considered for this analysis since it was assumed that wind blocking features beyond this distance would probably have minimal effect on the pheromone plume. Radius lines were drawn out of the trap at intervals of 10 degrees. If north is called 0 degrees and due east called 90 degrees, the average distance to wind blocking features north of the trap were calculated by averaging distances between the 280 and 80 degree positions inclusively. Likewise, average distance to south wind blocking features was calculated by averaging all distances between the 100 and 260 degree positions inclusively. Average for all directions was calculated by averaging the distances for all 36 radius lines.

Hectares of corn within the various radii away from the trap were calculated on the GRASS geographical information system. All plantings which at some point in the field season would be in one of the silking phases (0%-100% silking) on the same day as the trapped planting were called "same age" for the purposes of this model.

### Overview of Simulation Modeling Approach

The simulation model functions essentially as a filter which removes from the trap catch moths originating from plantings outside of the trapped planting. The model operates by calculating a trap modification value for every day of the trapping season and for every site. This modification value when multiplied times actual trap catch for that site/day produces a modified catch value. Figure 5 is a flow chart which shows how the modification value is calculated for every site/day. In order to determine this value, three map surfaces were created in the GRASS geographical information system. The modification value is calculated directly from a "contribution to catch" map surface. This map surface shows for all positions around the trap the likely relative contribution that location made towards the trap catch observed on that day. This map surface is the product of two other map surfaces: the pheromone emission response surface and the moth population surface. The emission response surface shows for all locations the likeliness that a moth positioned there will be captured by the trap within some time limit "T". The moth population surface shows the relative population for all positions around the trap. In order to calculate the pheromone emission response surface wind speed and direction needs to be determined for each site/day. For future discussions in order to distinguish the full model (illustrated in figures 11 and 12) from sub models, the full model will be referred to as the Trap Catch Modification Model.

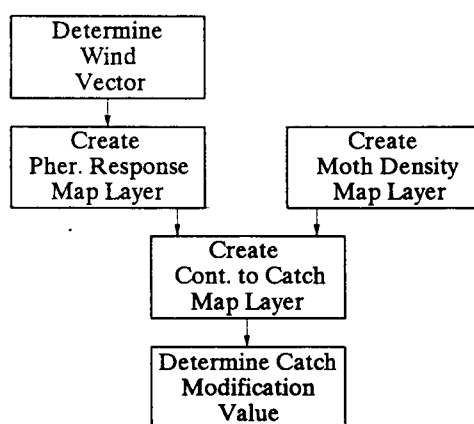


Figure 5. Processes Involved in Calculating Trap Catch Modification Value.

A UNIX script file was written that calculates a modified trap catch for every day and for every planting with damage information. This modified trap catch is

then summed up for all days between first tassel and first silk. The contents of the script file as well as C programs and script files accessed by it are listed in Appendix B and C. A flow chart of the script file is shown in figure 6. The file begins by determining what is the first and last dates for which 1) there is at least one planting between first tassel and first silk and 2) this planting had a trap that caught more than zero moths. Note: Since traps were checked every third day, daily moth catch was estimated by dividing the observed catch by three and assigning that value to all of the intervening days. Because of this, fractional moth catches are possible. With starting and ending dates established, the script file then generates a wind field for every intervening day. On each of these days and for every site with a trap catch greater than zero, the wind vector is determined from the previously calculated wind field. Using this wind vector, a pheromone emission response map layer is created within GRASS. Corn stages are determined for every planting and these are then used to determine likely relative moth concentrations. The map layer created from this is then multiplied by the pheromone emission response map layer to produce a "contribution to catch " map layer. Then for every planting in the site for which damage data is available, a modified trap catch is calculated and added to the cumulative catch for that planting. The final product of the script file is a file containing a modified cumulative catch for every planting . This can now be compared to damage to see if it correlates more strongly than the unmodified catch.

### Generating the Wind Field

In order to determine the wind speed and direction for each site/day, wind vectors had to be interpolated between locations where wind speeds and directions were known. The program AFWIND (Kunkle, 1988) was used to perform this interpolation. The model upon which the AFWIND program is based was developed at an Army Atmospheric Sciences Laboratory (Ball and Johnson, 1978) and was validated at the Air Force Geophysics Laboratory (Lanicci, 1985; Lanicci and Weber, 1986; Lanicci and Ward, 1987). The theory and equations for the model are contained in the above mentioned references. AFWIND takes wind speed and direction information from one or more point locations and generates a wind field over a user defined region. Information needed by the model includes terrain data

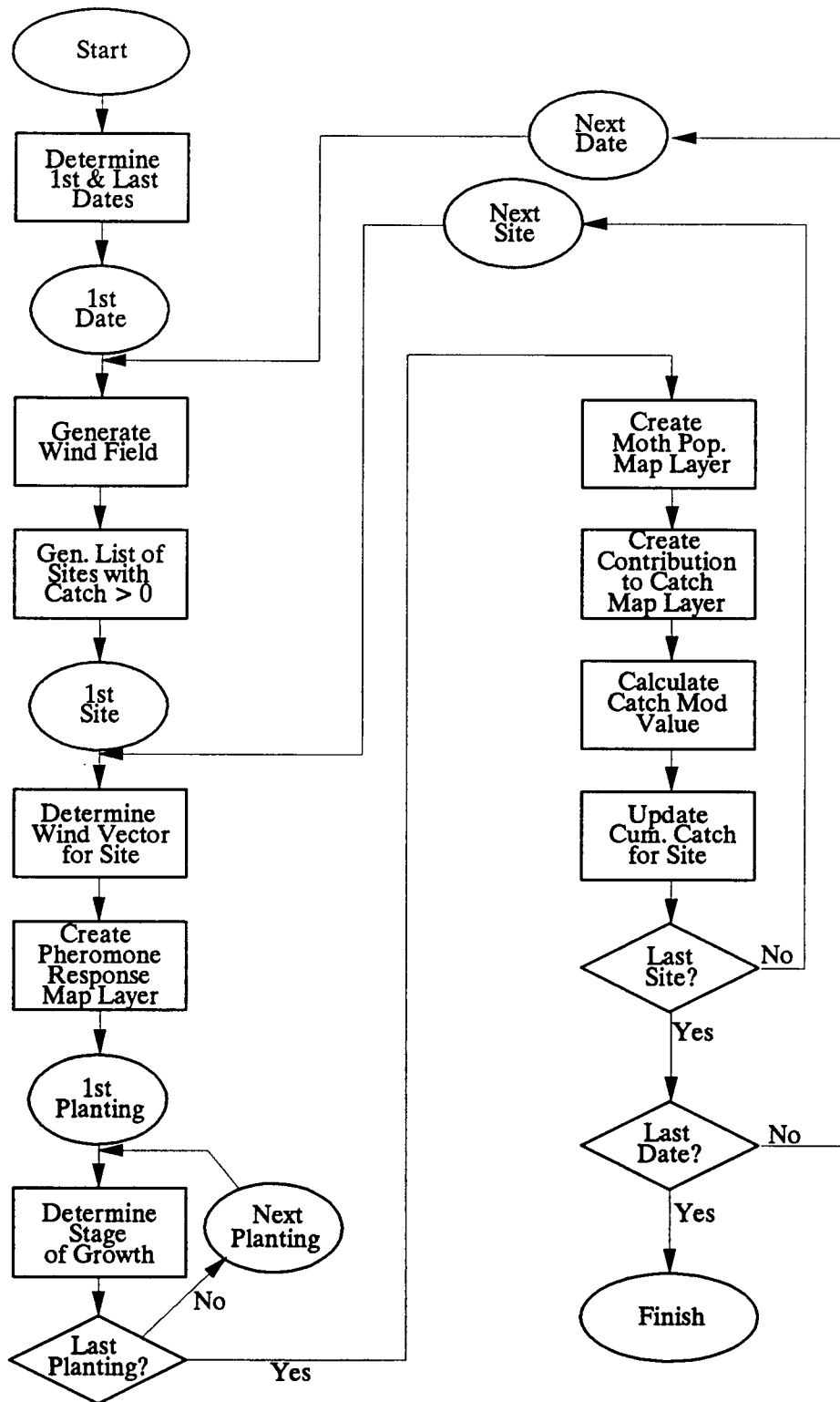


Figure 6. A Flow Chart Showing the Sequence of Events in the Trap Catch Modification Script.

showing elevations and surface roughness, a position fix for weather stations, a date and time, temperature, wetness, percent cloud cover, and ceiling height data.

A terrain file with a 36 by 75 (E-W by N-S) grid of elevation values (in meters) and with a spatial separation of 1,195 meters between grid points was used for AFWIND runs. This file was created by accessing USGS DEM files through GRASS. The region enclosed by this file was large enough to cover all of the trap sites. From this, AFWIND created 35 by 74 wind vector values at the same spatial resolution as the elevation grid points. AFWIND gives the user the option of either inputting a variable surface roughness file or assigning a single roughness value over the entire region. Surface roughness is some indication of differences in height between the tallest features on the landscape and the shortest and is measured in meters. Since no data was available for surface roughness over the entire region, a single roughness value of four meters was used instead. This was believed to constitute a compromise between the relatively even surfaces which would be found in agricultural areas versus what would be found in urban and forested areas.

I had some difficulty in obtaining suitable weather station data for AFWIND. The wind data available was from three airports (Corvallis, Eugene, and Salem) and from the Hyslop experiment station. All of these sources had problems. Airport data was recorded from 10 meters up, which was much higher than corn height. Hyslop data was recorded from approximately the right height, but was only recorded at a daily temporal resolution. Moth mating flights were assumed to take place mostly in the hours between 8 p.m. and 5 a.m. (Hsiao, 1978). Therefore conditions specific to that time period were desired for input into the AFWIND model. All of the climate file sources had many days where no data was collected. The remainder of this section is devoted primarily to explaining specific problems related to climate data and how these problems were resolved.

Because there were so many blanks in the source files, an alternate method of obtaining any input datum had to be included in the code of the script file. For wind data, all three airport's data files were inspected to see if wind data was available. The wind data from every available site was then entered into AFWIND. If it turned out that no wind data was available for any day, then seasonal average winds were used for all three sites. Seasonal average winds were calculated using data from every day between May 1 and September 30 that had non-blank data. Average wind speeds and directions were calculated as 229 m/min. from 308° (0° = N, 90° = E)

for Corvallis, 116 m/min. from 304° for Salem, and 59 m/min. from 327° for Eugene.

AFWIND also needs some indication of cloud cover. This is input as integer values from 0 to 8 with "0" indicating clear skies and "8" indicating completely overcast skies. The airport data reported sky cover as "CLR", "SCT", "BKN", and "OVC" to refer to cases of clear skies, scattered clouds, broken clouds, and overcast. Several such readings were usually available for any particular night. The script created one cloud cover value by assigning a 0 to clear, 3 to scattered clouds, 5 to broken clouds, and 8 to overcast skies. These values were then averaged and rounded out to produce a single integer value. If no cloud cover data was available then a value of "2" was input to AFWIND since the sky was mostly clear on summer evenings. Even though it would probably have been preferable to use a central location, such as Corvallis, for cloud cover data, Eugene data was used. Corvallis data was automatically collected by a ceilometer which could only measure up to 366 meters (1,200 feet). If clouds were above that height, then the Corvallis airport would record the sky cover as "clear" even if it was completely overcast.

For cloud type, AFWIND was looking for an integer value with "1" meaning high clouds, "2" meaning medium clouds, and "3" meaning low clouds. This was determined by averaging cloud height data from the Eugene airport file for the period from 8 p.m. to midnight. This data was recorded in hundreds of feet. If the average cloud height was less than 50, a "3" was assigned; if greater than 50 but less than 150, a "2" was assigned; otherwise a "1" was assigned.

For temperature, airport data was not used since it was collected for 10 meter height and therefore usually was too low. Hyslop data, which was collected approximately at corn height, was only measured in maximum and minimum temperatures per day. To estimate evening temperature at ground height a regression equation was calculated which related the mean evening temperature for airport locations to the maximum temperature. This equation, calculated for Fahrenheit (the scale used by all of these weather stations), was significant ( $p < .05$ ) and had an  $R^2$  of 0.61. The equation was:

$$\text{Av. Evening Temp.} = (\text{Max. Temp} * 0.41) + 33.12$$

This equation was then applied to the Hyslop maximum daily temperature to produce an estimate of the evening temperature at corn height.

For wetness, AFWIND expects one of two responses: "1" for wet and "2" for dry. For this, precipitation data from Hyslop (measured in 1/100 inches) was

used. If the average was above 10 then a "1" was input, otherwise a "2" was input. As a default, wetness was assumed to be "2" if no data was available.

### Creating the Pheromone Emission Response Map Layer

This model is modified from the SPERM (Sex Pheromone Emission Response Model) developed by Hartstack et al. (1976). However, the SPERM model relies in part on the Sutton plume model (Sutton, 1953) which requires information on release rates from the plume source as well as vertical and horizontal variance in plume position caused by turbulence. This kind of information was not available for the corn/corn earworm system of Oregon and so modifications were made to the model to get around these problems.

The pheromone response map layer is calculated as the product of two variables: 1) excess search time and 2) likelihood of plume detection. Figures 7 and 8 illustrate how these variables are calculated.

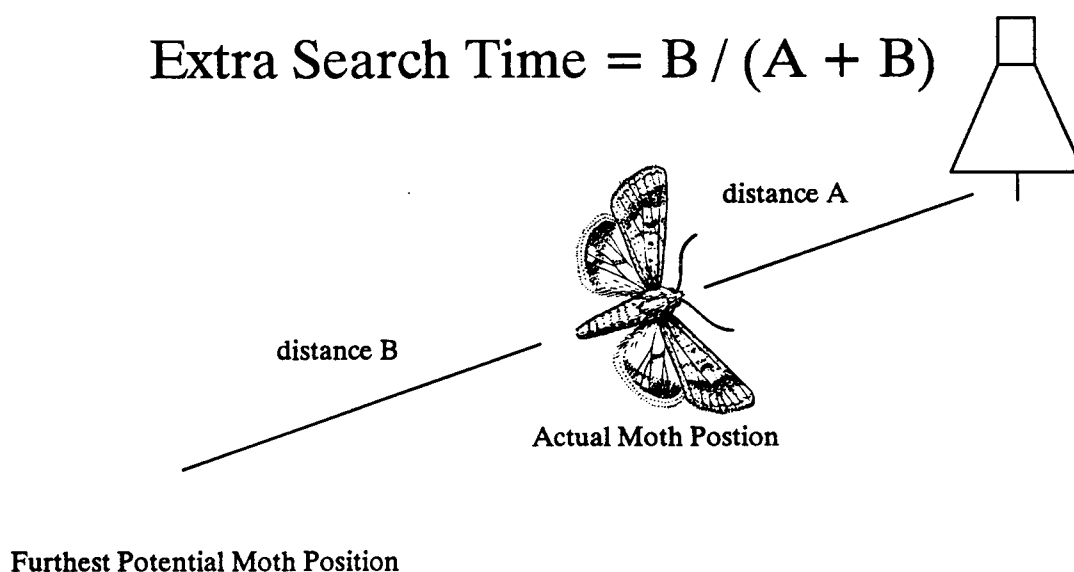
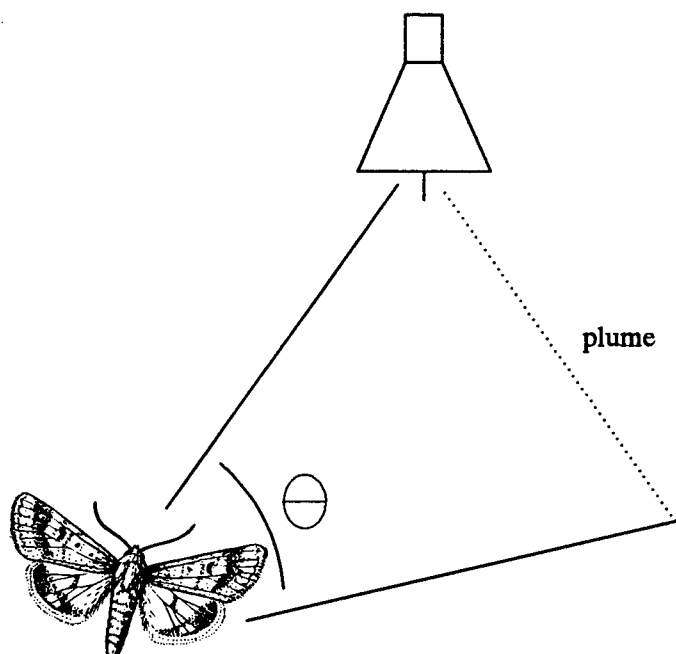


Figure 7. How to Calculate Extra Search Time.



$$\text{Likelihood of Plume Detection} = \Theta / 2\pi$$

Figure 8. How to Calculate Likelihood of Plume Detection.

Extra search time indicates how much extra time will be available to the moth within some time limit "T" to search for the plume. Moths positioned so far away as to barely be able to reach the trap within time T will have almost no excess search time. Moths positioned next to the trap will have relatively large amounts of excess time. The actual flight path taken by the moth is calculated as a summation of the direction vector taken by the moth and the direction vector of the prevailing wind (figure 9). Moths are assumed in this model to fly at a rate of 180 m/min. This is the maximum flight rate used by Hartstack et al. (1976) for the cabbage looper, *Trichoplusia ni* (Hubner). It was assumed that this speed would be a reasonable approximation for earworm moth speed since the cabbage looper is also a moth of the family Noctuidae and similar in size to the corn earworm. Excess search time is calculated by drawing a straight line through the trap and through the moth position. The farthest position on that line that the moth could be and still reach the trap within time "T" (FP) is then found. Once this position is determined, the excess search time is calculated by dividing the distance from moth to FP by the distance



between the trap and FP. The maximum excess time value therefore is 1 for moths positioned at the trap and is 0 for moths positioned far from the trap.

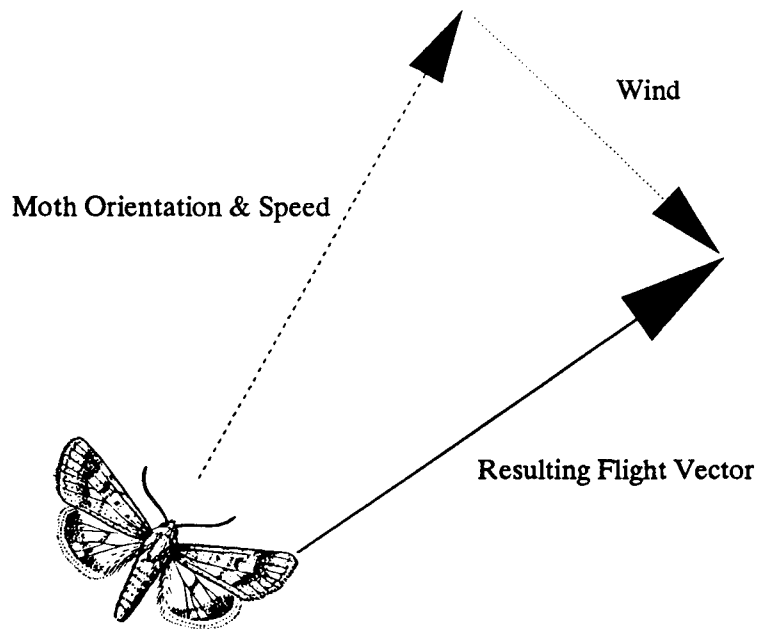


Figure 9. Actual Moth Flight Vectors are Calculated as the Sum of the Wind and Moth Orientation Vectors.

The likeliness of plume detection is calculated as the proportion of possible directions that the moth could take which would result in its crossing the pheromone plume. Looking at Figure 8, it is calculated as the ratio of  $\theta/2\pi$ , where  $\theta$  is the angle between lines A and B. Line A goes from moth to trap. Line B goes from moth to the farthest downwind position where the plume is still concentrated enough to elicit a response from the moth (active space). The likeliness of plume detection has a maximum of 0.5 for moths positioned next to the pheromone plume and a minimum of 0 for moths positioned either at long distances away from the trap or for moths positioned outside of the plume active space and directly up or downwind of the trap.

Hartstack et al. were able to use the Sutton plume model to estimate the active space. It produces an elliptical area with the pheromone trap positioned on one vertex of the ellipse and with the major axis of the ellipse oriented with wind direction on the downwind side of the trap. Since I did not have access to the kind

of information required to produce this kind of active space model, I modeled the plume as a line moving downwind of the trap. Initially, a plume length of 75 meters was assumed.

$$x_{\max} = \frac{\left[ \frac{T \cdot \sqrt{[x^2 \cdot M^2] - [y^2 \cdot W^2] + [y^2 \cdot M^2]}}{x} - W \cdot T \right]}{\left[ \left[ \frac{y^2}{x^2} \right] + 1 \right]}$$

$$y_{\max} = \frac{\left[ \frac{T \cdot \sqrt{[x^2 \cdot M^2] - [y^2 \cdot W^2] + [y^2 \cdot M^2]}}{y} - (x \cdot W \cdot T) \right]}{\left[ \left[ \frac{x^2}{y^2} \right] + 1 \right]}$$

$$\text{Dist}_{\max} = \sqrt{[x_{\max}]^2 + [y_{\max}]^2} \quad \text{Dist}_{\text{moth}} = \sqrt{x^2 + y^2}$$

$$\text{ExtraSearchTime} = \left[ 1 - \left[ \frac{\text{Dist}_{\text{moth}}}{\text{Dist}_{\max}} \right] \right]$$

$$\text{Theta} = \frac{\arccos \left[ \frac{[x^2 + y^2] + [(x-L)^2 + y^2] - L^2}{2 \cdot \sqrt{[x^2 + y^2]} \cdot \sqrt{[(x-L)^2 + y^2]}} \right]}{(2 \cdot \pi)}$$

$$\text{LikelinessOfPlumeDetection} = \frac{\text{Theta}}{(2 \cdot \pi)}$$

$$\text{LikelinessOfCapture} = \text{LikelinessOfPlumeDetection} \cdot \text{ExtraSearchTime}$$

Figure 10. Equations used in the Calculation of Likeliness of Capture.  $x$  = moth  $x$  position.  $y$  = moth  $y$  position.  $x_{\max}$  = maximum  $x$  position along the trap/moth orientation that moth could be and still reach the trap in time  $T$ .  $y_{\max}$  = maximum  $y$  position.  $T$  = Search Time.  $M$  = Moth Speed.  $W$  = Wind Speed.  $L$  = Plume Length. Theta is the angle between the moth/trap line and the moth/max. plume dist. line (Illustrated in Fig. 8).

The final pheromone emission response value produced by the model was the product of the excess search time ratio times the likeliness of plume detection. Actual equations used by the model are shown in Figure 10. This model is not intended to produce an actual measure of trap-capture-likeliness, but rather is intended to give some idea of the relative likeliness compared to other positions surrounding the trap. Figures 11 and 12 show examples of what this capture likeliness surface looks like for both slow and fast winds. In these figures, darker shadings indicate greater likeliness of capture.

The response surface created by the ER program was generic as far as wind direction was concerned. All map surfaces created by it assumed a wind heading directly down the x axis. Several steps were required to go from this directionless response surface to the final map layer in GRASS for which the emission response map layer would be oriented with the prevailing wind direction. The ER program output the response field in a PGM file format compatible with the PNM utilities developed by Jef Poskanzer for Sun Release 4.1 UNIX systems. These utilities included programs which could rotate the response field to any angle. The wind direction for the site was then used with the rotation utility to produce a response field PGM file of the correct orientation which then could be converted to a Sun Raster file (using `pnmtoastr`) and input into GRASS (using `r.in.sunrast`). These pheromone emission response fields were loaded into the same map location as the digitized corn planting maps.

#### An Alternative Emission Response Layer Model

The emission response model described above assumes that moth flight is directionally random when not in contact with a pheromone plume. This assumption is most apparent in the calculation of likeliness of plume detection, which is calculated as  $\theta$  (the angle describing all possible directions where the moth will cross the plume) divided by  $2\pi$  (set of all possible directions). If moths outside the influence of any plume behave in a manner that maximizes the likelihood of finding a plume, perhaps they restrict their movements to some subset of the possible  $2\pi$  directions. To consider this possibility I wrote an alternative version of the emission response model which assumes that moths outside the influence of any plume tend to move cross-wind in order to maximize the likelihood of encountering a plume. For

this model, an additional parameter needs to be input, which is the possible range of crosswind angles through which a moth will move ( $\Theta_2$ ; see Figure 13). Now the likeliness of plume detection is calculated as  $\Theta_1/2(\Theta_2)$ . Where  $\Theta_1$  is that portion of the  $2(\Theta_2)$  directions that will result in the moth crossing the plume. In every other way, the alternative emission response layer model functions the same as the original model.

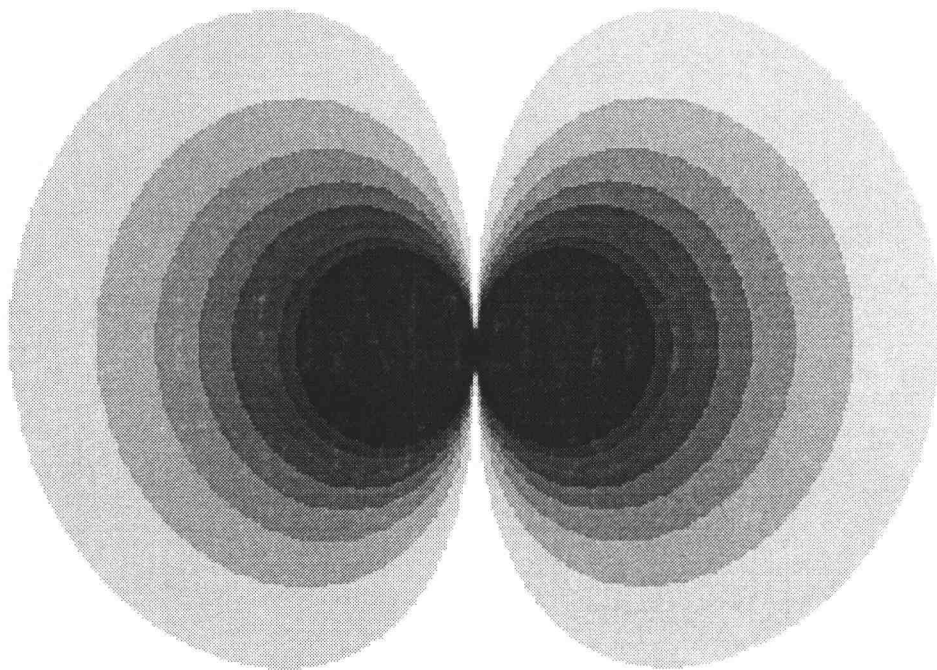


Figure 11. Image of the "Likeliness of Capture" Map Layer. For this image a 5 meter/minute wind is blowing from the top side. A 125 meter plume active space is used. This image is 5,000 meters along each side. Likeliness of capture is indicated by shading, with dark locations having a relatively high likeliness of capture and light areas having a low likeliness of capture. The pheromone source is located on the top side of the dark region in the center of the image.

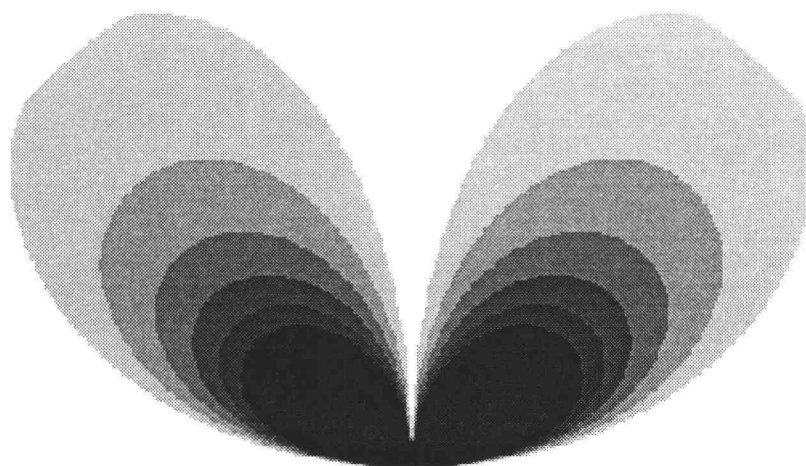
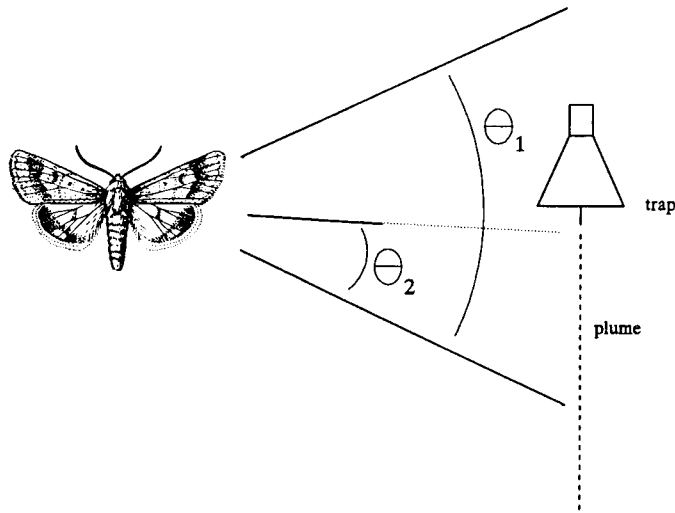


Figure 12. Image of the "Likeliness of Capture" Map Layer. For this image a 175 meter/minute wind is blowing from the top side. A 125 meter plume active space is used. This image is 5,000 meters along each side. Likeliness of capture is indicated by shading, with dark locations having a relatively high likeliness of capture and light areas having a low likeliness of capture. The pheromone source is located on the top side of the dark region in the center of the image.



$$\text{Likelihood of Plume Detection} = \theta_2 / 2 \theta_1$$

Figure 13. How to Calculate Likelihood of Plume Detection for the Alternative Emission Response Model.

#### Creating the Moth Population Map Layer

Corn earworm moths tend to be drawn more strongly to certain growth stages of host plants. For example earworm moths are considerably more attracted to silking corn than they are to tasseling or leaf stage corn (Johnson et al., 1975). Johnson et al. were able to quantify relative ovipositional preferences for several stages of corn, tobacco, cotton, and soybeans. Assuming that ovipositional preferences give an indication of moth population concentrations, Johnson's values were used in my model to indicate moth populations for all plantings around the pheromone trap given their stage of development. Moth concentration values used in my model for each corn stage are listed in Table 2.

Table 2. Relative Concentrations of Moths Based on Corn Phenology. Values based upon attractance values measured by Johnson et al. (1975).

Corn Stages	Relative Conc.
1 Leaf - 8 Leaves	1
9 Leaves	2
10 Leaves	9
11 Leaves	13
0" - 10" Tassels	16
0% - 30% Silk	22
40% - 60% Silk	21
70% - 100% Silk	3
10% - 40% Brown Silks	8
50% - 100% Brown Silks	2
Post Harvest	0

Corn development was modeled using a simple degree-day accumulation model. For each day, the degree-day value was calculated by the following algorithm:

If Max. < UPPER and Min. > LOWER:  $(\text{Max.} + \text{Min.})/2 - \text{LOWER}$   
 If Max. > UPPER:  $(\text{UPPER} + \text{Min.})/2 - \text{LOWER}$   
 if Min. < LOWER:  $(\text{Max.} + \text{LOWER})/2 - \text{LOWER}$

Where UPPER and LOWER are temperature development thresholds. For each year of the study UPPER and LOWER threshold values were optimized to produced the minimum squared error (days) for 44 corn development stages. For the optimization all combinations of UPPER threshold values from 30 to 100°F (10°F intervals) and LOWER threshold values from 20 to 80°F (10° intervals) were investigated. Taking the optimal UPPER and LOWER combination thus produced a better combination was searched for by exploring all UPPER and LOWER temperature within 10°F of

this optimal at 1° intervals. The optimal (with the lowest squared error) combination thus found was subsequently used to model plant development for all sites for that year. Optimal LOWER and UPPER threshold values as well as mean cumulative degree-day to each corn stage for 1990 and 1991 are shown in tables 3 and 4.

Table 3. Cumulative Degree Days for 44 Corn Development Stages based Upon a Lower Threshold of (40°F) and an Upper Threshold of (98°F). This is the model which produced the lowest squared error for days in 1990.

Stage Num.	Stage Name	Min. Deg. Day Accum. for Stage
1	1st Leaf	163.0
2	2nd Leaf	232.2
3	3rd Leaf	328.5
4	4th Leaf	431.2
5	5th Leaf	551.0
6	6th Leaf	642.5
7	7th Leaf	785.5
8	8th Leaf	943.7
9	9th Leaf	1076.2
10	10th Leaf	1202.3
11	11th Leaf	1244.1
12	0" Tassels	1327.7
13	1" Tassels	1411.3
14	2" Tassels	1422.0
15	3" Tassels	1432.7
16	4" Tassels	1486.3
17	5" Tassels	1509.4
18	6" Tassels	1532.5
19	7" Tassels	1592.2
20	8" Tassels	1651.8
21	9" Tassels	1656.3
22	10" Tassels	1704.7



Table 3. (Continued)

23	0% Silk	1753.1
24	10% Silk	1758.4
25	20% Silk	1783.2
26	30% Silk	1807.9
27	40% Silk	1857.1
28	50% Silk	1876.8
29	60% Silk	1896.6
30	70% Silk	1916.3
31	80% Silk	1954.9
32	90% Silk	2013.0
33	100% Silk	2071.0
34	10% Brown	2174.8
35	20% Brown	2190.6
36	30% Brown	2206.3
37	40% Brown	2222.1
38	50% Brown	32229.1
39	60% Brown	2293.2
40	70% Brown	2372.1
41	80% Brown	2398.3
42	90% Brown	2436.8
43	100% Brown	2466.6
44	Harvested	2811.4

Table 4. Cumulative Degree Days for 44 Corn Development Stages based Upon a Lower Threshold of (44°F) and an Upper Threshold of (90°F). This is the model which produced the lowest squared error for days in 1991.

Stage Num.	Stage Name	Min. Deg. Day Accum. for Stage
1	1st Leaf	127.2
2	2nd Leaf	233.4
3	3rd Leaf	253.3
4	4th Leaf	336.9
5	5th Leaf	388.4
6	6th Leaf	471.2
7	7th Leaf	522.5
8	8th Leaf	593.9
9	9th Leaf	700.5
10	10th Leaf	827.3
11	11th Leaf	920.3
12	0" Tassels	1070.5
13	1" Tassels	1090.3
14	2" Tassels	1141.4
15	3" Tassels	1164.2
16	4" Tassels	1176.6
17	5" Tassels	1250.3
18	6" Tassels	1263.9
19	7" Tassels	1277.4
20	8" Tassels	1289.2
21	9" Tassels	1313.9
22	10" Tassels	1338.5
23	0% Silk	1367.4
24	10% Silk	1396.3
25	20% Silk	1427.2
26	30% Silk	1458.0
27	40% Silk	1488.9
28	50% Silk	1493.0
29	60% Silk	1497.1
30	70% Silk	1501.2

Table 4. (Continued).

31	80% Silk	1505.3
32	90% Silk	1509.3
33	100% Silk	1593.2
34	10% Brown	1718.6
35	20% Brown	1752.5
36	30% Brown	1761.7
37	40% Brown	1770.7
38	50% Brown	1780.1
39	60% Brown	1789.6
40	70% Brown	1799.0
41	80% Brown	1824.6
42	90% Brown	1888.4
43	100% Brown	1903.2
44	Harvested	2232.7

Since the corn stage for every planting was established on at least one day during the field season (the day in which the site was mapped) and since max./min. temperature data was available for all days through the field season, it was possible to estimate the corn stage for all plantings on any day. Figure 14 shows the map layer of relative moth concentrations produced in GRASS for one particular site. Locations with lighter shadings have higher concentrations of moths.

#### Producing the Trap Catch Adjustment Value

The trap adjustment value is multiplied with the actual trap catch value to produce a modified catch for any site/day. This trap adjustment value is intended to be an estimate of the proportion of moths from the trap catch that came from the planting for which a damage estimate is desired. In order to calculate it, a "Contribution to Catch" map surface needs to be created in the geographical information system. This map layer represents the relative contribution that each location made towards the trap catch and can be calculated for each pixel by multiplying the population map layer value times the likeliness of catch map layer

value. An example of this new map layer is shown in Figure 15. The trap adjustment value is the proportion of the total contribution to catch values coming from the planting of interest. As shown in Figure 16, this can be calculated by summing contribution to catch values for all pixels within the map location and dividing by the total sum of contribution to catch values over the entire map.

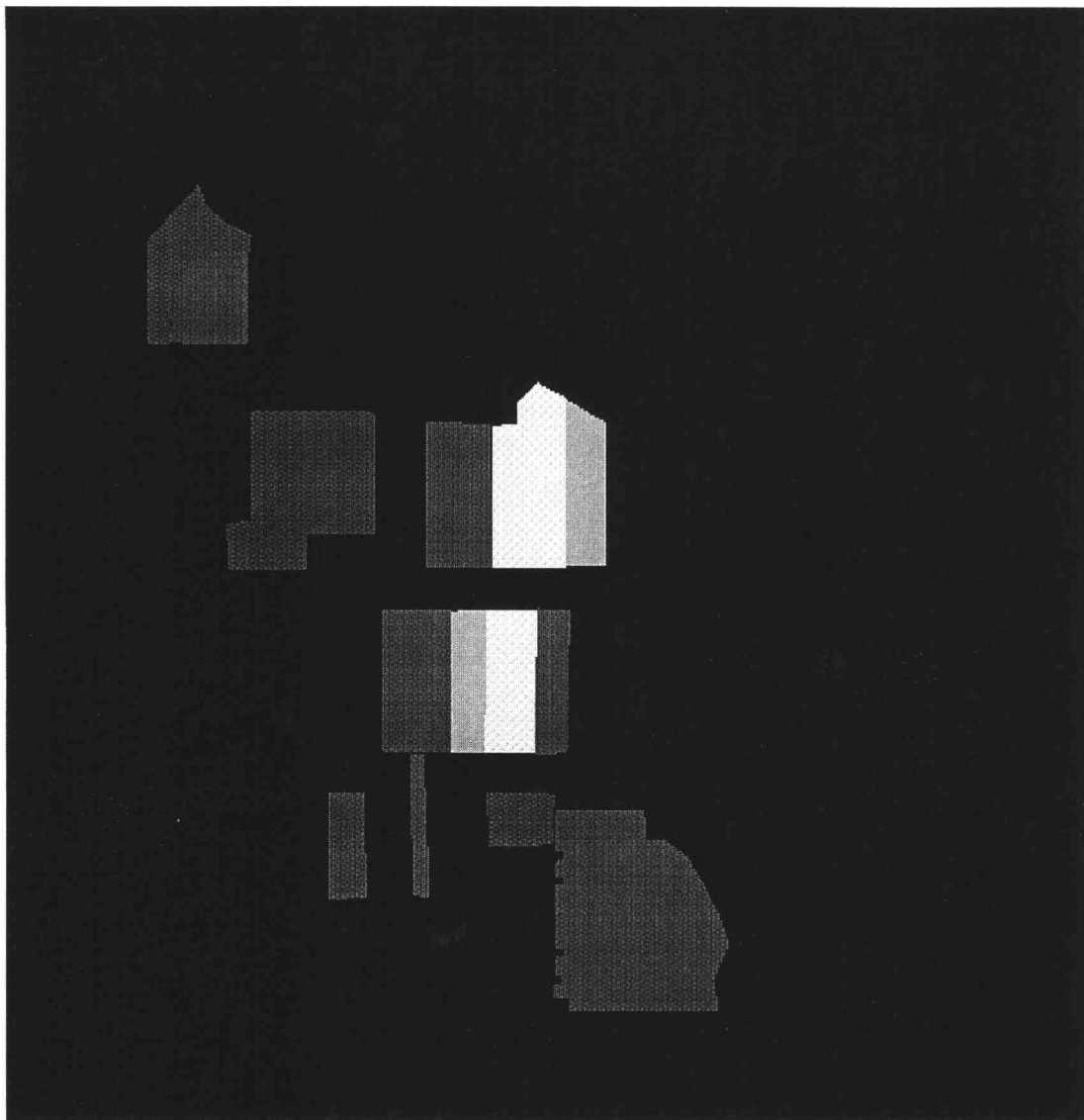


Figure 14. Example of a Map Layer Showing Relative Concentrations of Moths. Lighter locations are in stages of corn development which are more attractive to corn.

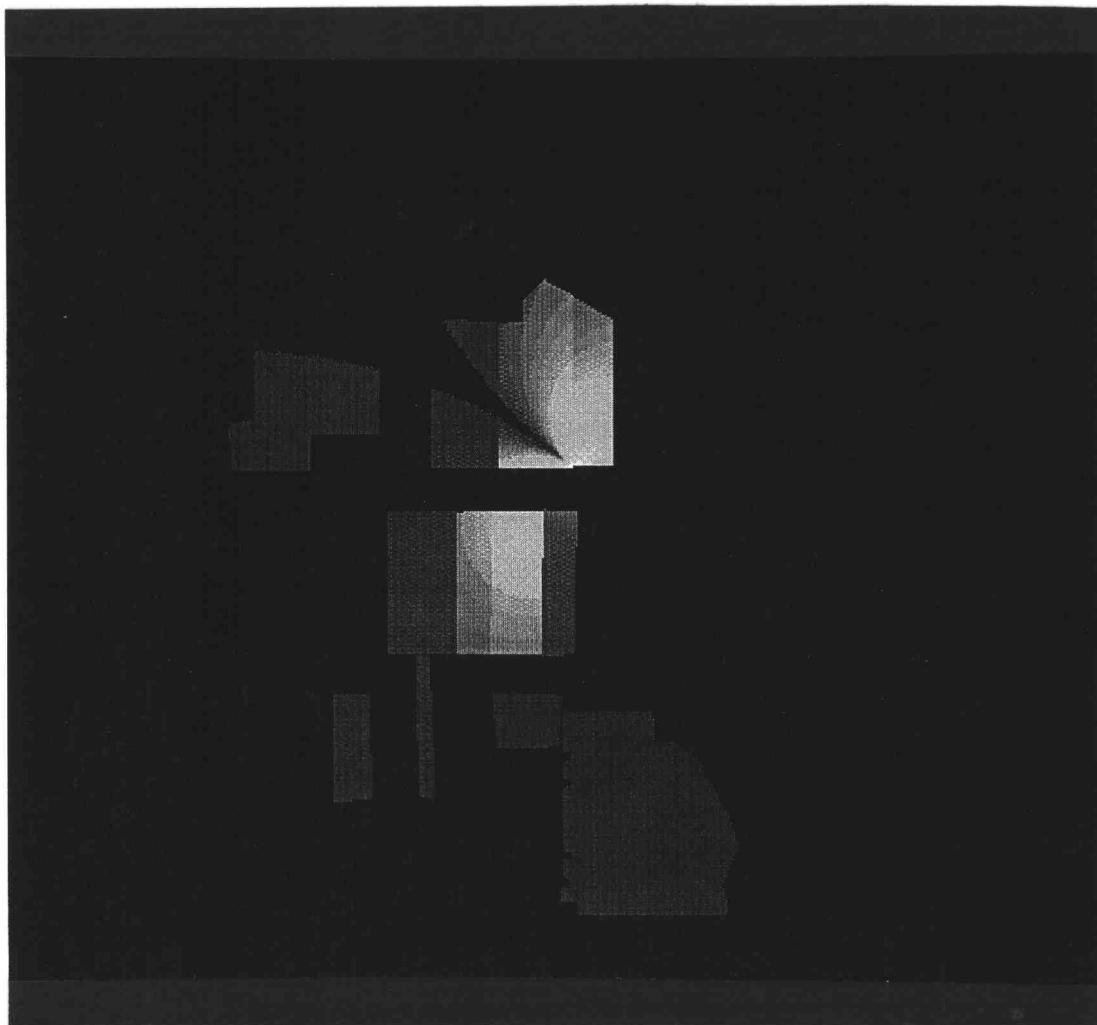


Figure 15. Example of a Map Layer Showing Relative Contribution to Catch for Locations Surrounding the Pheromone Trap. For this Image, the Wind is Coming from the Upper Left Corner, the Pheromone Trap is located in the Center, and the Lightness of Shading Indicates the Likelihood of Capture. The Location Shown in this Map is the Same as the one in Figure 14.

$$\text{Proportion of Trap Catch Coming from Planting A} = \frac{\sum_{\text{Planting A}} \text{Contribution to Catch}}{\sum_{\text{All}} \text{Contribution to Catch}}$$

Figure 16. Method used to calculate the trap catch adjustment value, which is meant to be a measure of the proportion of the trap catch coming from any particular planting.

### Another Alternative to the Model Which Considers Wind Blocking Features

It was hard to imagine that corn plantings behind wooded areas, tree rows, or abrupt hills would have much of an influence on the trap catch observed in the trapped plantings. Therefore, another alternative to the basic trap catch modification model was to have it run so as not to consider such wind-blocked locations. This was done by using a program within the GRASS geographical information system called `r.los`. This program takes as input a point location to use as an observation site and a terrain map surface. The output is a map surface showing all locations within site of the observation point. Using the trap as the observation point and the wind blocking feature map as the terrain surface, I was able to create a map showing all locations surrounding the trap that were not isolated from the trapped planting by wind blocking features. This map surface could be used as a mask to remove from consideration wind-blocked plantings and the model could then be run just as it has been described above.

#### 4. Results

Moth flight patterns, as measured by pheromone traps, did not display any unusual patterns in either 1990 or 1991. As had been observed in previous years (Figure 17), there was a flight peak starting in early August, peaking in late August or early September, and dropping to pre-peak levels near the end of September. Compared with 1988 and 1989, moth flight levels were not unusually high or low, though neither 1990 nor 1991 had peak levels as high as was observed in 1988. One difference between 1990 and 1991 moth flights versus 1988 and 1989 was the lack of any pre-August flight peaks. There was a distinct peak in 1989 starting around May 26 and continuing until July 1. In 1988 traps were not placed until July 10, but still the tail end of what appears to be an early season moth peak can be seen. In both 1990 and 1991, some traps were placed by the first week of May. The first moth was captured on May 8 in 1990 and on June 10 in 1991. The June 10 first-capture in 1991 is unusually late and undoubtedly results from a wet and cool spring. From the date of first capture until population peaks in August sporadic captures of moths occurred at steadily increasing rates in both 1990 and 1991.

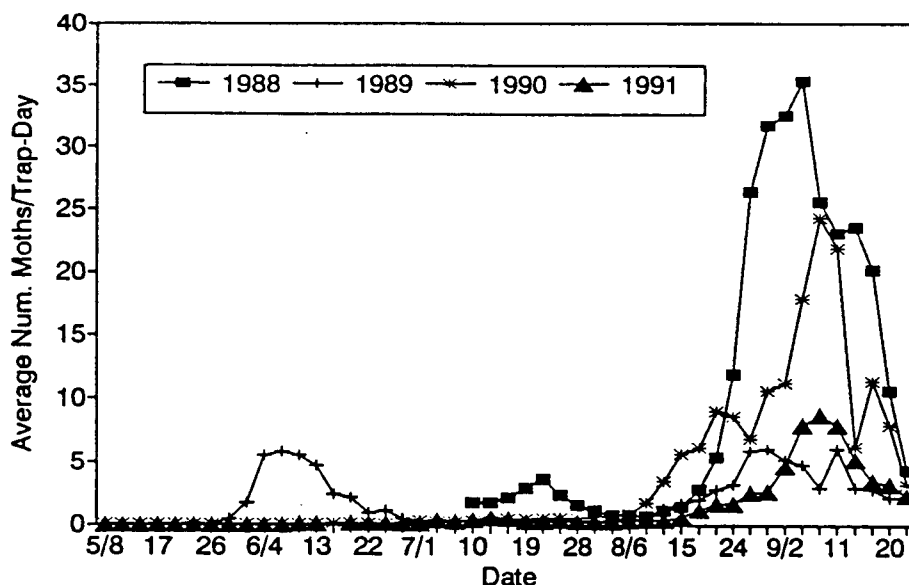
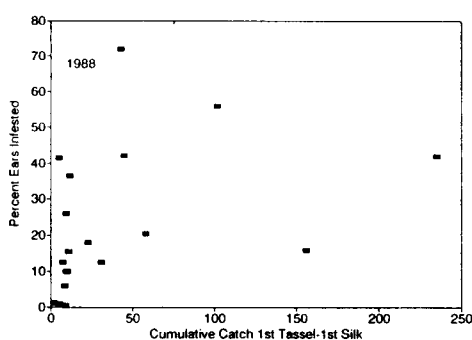
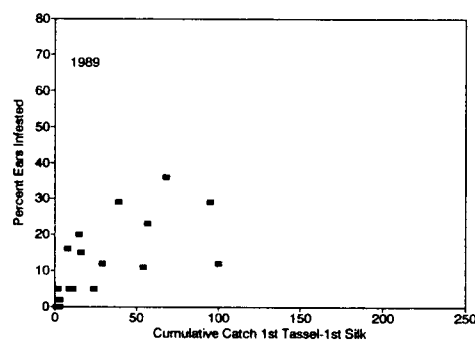


Figure 17. Average catch/day from pheromone traps 1988-1991.

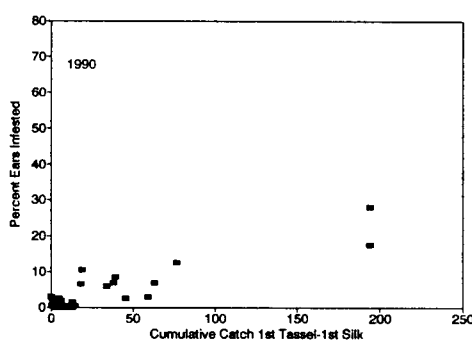
Damage levels in 1990 and 1991 were very low. The majority of sites in both years had less than 5% infestation levels and no site had sustained enough damage to warrant the use of pesticides. Figures 18a-18d show scatter plots of trap catch versus damage levels for years 1988 through 1991. Though 1990 had two sites with damage levels nearly as high as the maximum damage sites in 1989, for the majority of sites damage was quite low. Trap catch levels in 1990 generally were comparable with 1989 and in fact two sites in 1990 had higher cumulative catches from 1st tassel to first silk than were observed in any sites in 1989. Both cumulative trap catch and damage levels in 1991 were extremely low, though daily average trap catch levels were comparable to 1989 levels (Figure 17). Correlation between cumulative trap catch and damage is not very high in 1990, though it is the highest observed between 1988 and 1991. Correlation between cumulative trap catch and damage is very low in 1991.



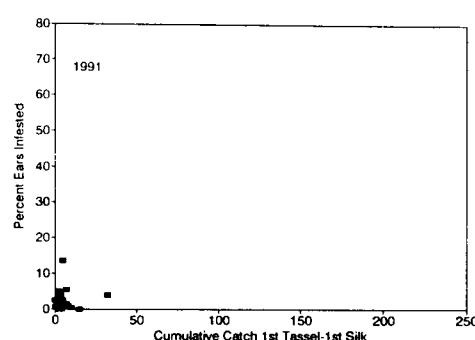
a) 1988



b) 1989



c) 1990



d) 1991

Figure 18. Scatter plots of trap catch versus damage for 1988-1991. Trap catch is the cumulative trap catch from 1st tassel to 1st silk. Each dot represents one trapped site.



### Regression Analysis

A stepwise regression analysis was performed considering the 20 potential independent variables outlined in the Materials and Methods section. A supervised approach was followed to ensure that no more than one measure each of corn area and distance to wind blocking features would be included as independent variables. As was done by Coop et al. (1992), a  $\text{sine}^{-1}$ (square-root) transformation was performed on the y variable (proportion of damaged ears). For 1990, the results once again included trap catch and date of first silk as was observed by Coop et al. (1992), but this time hectares of corn within 2.0 kilometers of the trap and average distance on the north side of the trap to wind blocking features (WBF) were also included in the model (Table 5). Regression coefficients for all four input variables were significant ( $P < 0.05$ ). The regression model itself was significant ( $P = 0.000$ ) and had an  $R^2$  of 0.82. A regression model from 1990 data that only included trap catch and date of silking as input variables had an  $R^2$  of 0.72, therefore the spatial input parameters provided a substantial improvement to the model. As was observed by Coop et al., the regression coefficients for both cumulative trap catch and date of first silk were positive. The regression coefficient for corn area was negative indicating that larger acreage's of corn near the trap act to reduce the expected damage levels. The regression coefficient for the average distance to wind blocking features also had a negative sign indicating that the farther away north wind blocking features were from the trap the more expected damage should be lowered.

The stepwise regression analysis had a markedly different result for 1991 data (Table 6). The only variable that could be included in the model was the date of first silk. All of the spatial variables and trap catch as well provided no significant improvement to the model. Though the one variable model was significant ( $P = 0.004$ ), the  $R^2$  value was only 0.29.

Table 5. Four variable model for 1990, including spatial input variables estimated by stepwise least square multiple regression. Dependent variable =  $\text{Sin}^{-1}(\text{Sqrt}(\text{proportion infested ears}))$ . Data collected from (n=30) corn plantings monitored in 1990.  $R^2=0.82$ . Model  $P=0.000$ . "1st Silk" is the date on which silking is first noted. "Corn Area" is the number of hectares of corn within 4.0 kilometers of the trap. "WBF" is the average distance on the north side of the trap to a wind blocking feature. "Trap Catch" is the cumulative trap catch from 1st tassel to 1st silk (square root(x +0.5) transformed).

Independent Variable	Reg.Coeff.	SE	t value	P
Intercept	-0.43796	0.28432	-1.54	0.136
1st Silk	0.00284	0.00137	2.08	0.048
Corn Area	-0.00041	0.00016	-2.55	0.018
WBF	-0.11737	0.05445	-2.16	0.041
Trap Catch	0.27140	0.00512	5.30	0.000

Table 6. One variable model for 1991, estimated by stepwise least square multiple regression. Dependent variable =  $\text{Sin}^{-1}(\text{Sqrt}(\text{proportion infested ears}))$ . Data collected from (n=27) corn plantings monitored in 1991.  $R^2=0.29$ . Model  $P=0.004$ . "1st Silk" is the date on which silking is first observed in the corn planting.

Independent Variable	Reg. Coefficient	SE	t value	P
Intercept	-0.90615	0.32255	-2.81	0.010
1st Silk	0.00472	0.00147	3.21	0.004

#### Testing the Simulation Model: a Hypothetical Example

As a test of the simulation model, several simplified hypothetical corn planting patterns were input and the trap modification ratios produced by the model

were noted. For these hypothetical situations extreme conditions were considered for: 1) the degree of isolation of the trapped planting, 2) the size of the trapped planting, 3) the age of the trapped planting relative to surrounding plantings, 4) location of the trap within the field, and 5) the speed of the wind. Two scenarios were considered for degree of isolation, an isolated trapped planting and a trapped planting completely surrounded by corn. Two scenarios were considered for planting size, a large trapped planting (by the standards of plantings observed in 1990) versus a small planting. Three relative age scenarios were considered: 1) the trapped planting is an early planting and surrounding corn plantings are late plantings; 2) the trapped planting and surrounding plantings are approximately the same age; and 3) the trapped planting is a late planting and the surrounding plantings are early. Two scenarios were considered for trap placement; upwind and downwind traps. Two scenarios were considered for wind speed; nearly still winds and winds that are almost the maximum speed within which moths will fly. All 24 possible combinations of the above mentioned scenarios (2 wind speeds X 2 planting sizes X 2 trap locations X 3 relative ages of plantings) were run for plantings surrounded by other corn. Only one run of the isolated corn situation was done since all were expected to result in a catch modification ratio of 1. Looking back at figure 16, it can be seen why this is so. If planting "A" is the only planting to be considered, the ratio shown in Figure 16 will calculate to 1.

In order to run the scenario combinations, 4 map layers (small vs large central planting and upwind versus downwind trap) had to be created within GRASS. The small planting maps consisted of a square 4.41 ha planting positioned so that the central trap position was either 65 meters in on the upwind field side or 65 meters in on the downwind side (Figures 19a and 19b). The large planting maps consisted of a square 39.69 ha planting positioned so that the trap was either placed 65 meters on either the upwind or the downwind side (Figures 19c and 19d).

The four map layers shown in figure 18 could be altered to describe any of the relative corn age combinations desired using reclassification utilities within GRASS. For example, to describe an isolated planting, the area outside the central square could be classified as "0" (non corn) and the square itself would be assigned a non-zero numerical attribute describing its degree day development stage on August 5th (as is done in the trap modification model for actual site maps). To describe a planting surrounded by other corn plantings, the central square could be

assigned its degree day development value and the area outside the central square could be assigned its own degree day development value which could be different or

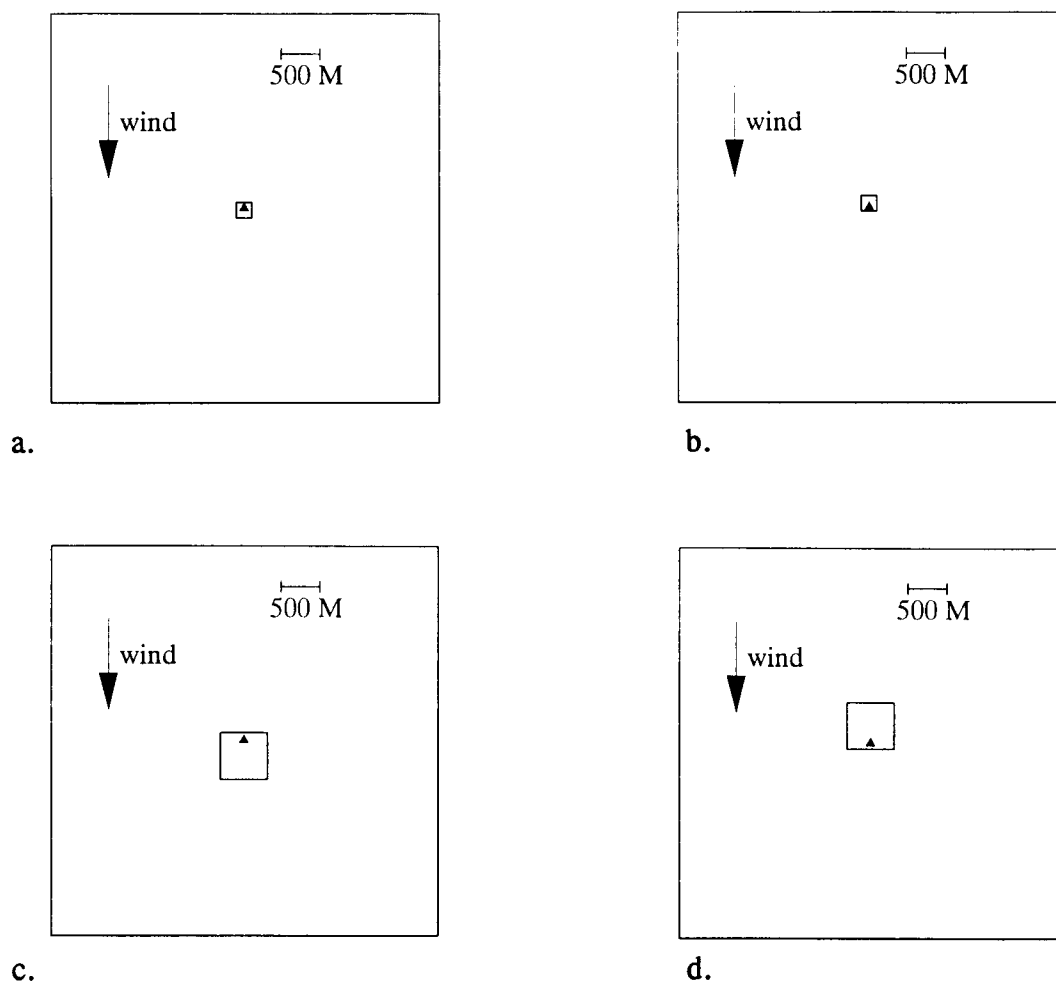


Figure 19. Map layers for 4 hypothetical corn planting situations: a) small planting with a trap placed on the upwind side of the field, b) a small planting with a trap placed downwind, c) a large planting with a upwind trap, and d) a large planting with a downwind trap. The square in the center represents the location of the planting. The triangle within the square represents the pheromone trap.

the same as the central square. For runs of the model where the central planting was to be young relative to the surrounding corn, the central planting was assumed to start tasseling on August 9th and to start silking on August 24th. On the August 9th

starting date the surrounding corn was assumed to have 70% brown silks. For runs of the model where the central planting and surrounding corn were to be the same age, both were assumed to be early plantings and to start tasseling on July 7 and start silking on July 18. For runs of the model where the central planting was assumed to be old relative to surrounding plantings, it was assumed to start tasseling on July 7 and start silking on July 18. On the July 7 starting date surrounding corn was assumed to be in the 2 leaf stage. The dates and timings chosen for these runs correspond to what was observed for earliest and latest plantings in 1990. Maximum and minimum temperature data from 1990 were used to update the corn development stages for runs of the model.

Wind was always assumed to come directly from the north. A wind speed of 5 m/min was chosen for slow winds and a wind speed of 175 m/min was chosen for fast wind speeds. The likeliness-of-catch map surfaces created by these two extremes of wind speed are shown in Figures 11 and 12.

As expected, the one run for an isolated corn planting yielded a trap catch modification ratio of one. Results for plantings that were surrounded by corn are shown in Table 7. The model produced catch modification ratios for every day between 1st tassel and 1st silk of the center planting, but these values never changed during that period. Therefore only a single value is listed in Table 7 for each scenario combination.

Table 7 shows that the model functioned as expected. As noted in the section titled "Producing the Trap Catch Adjustment Value" and illustrated in Figure 16, in order to calculate the trap modification ratio we need to divide the sum of contribution to catch values within the planting by the sum over all locations. "Contribution to catch" is the product of population X likeliness-of-catch levels for every pixel location. Increasing the size of the planting should increase this value since there will be more pixel locations from which values can be added to the within-planting sum (an increase in the numerator in Figure 16). All examples from Table 7 which differ only in the size of the central planting consistently show a larger trap modification ratio for plantings of larger size. For example, the SUOS combination (Small planting, Upwind trap, Older central planting, Slow wind) produced a catch modification ratio of 0.5675 while the LUOS combination produced a catch modification ratio of 0.7887.

Table 7. Trap catch modification values for hypothetical scenarios for a single central planting surrounded by other corn plantings. "Size of Planting" refers to the area taken up by the trapped (center) planting. "Side of Field" refers to the position of the pheromone trap within the center planting. "Relative Age" refers to the development stage of the center planting relative to surrounding plantings. "Wind" refers to wind speed (5 meters/min. = slow; 175 meters/min. = fast). "Mod. Ratio" refers to the trap catch modification ratio produced by the model.

Size of Planting	Side of Field	Relative Age	Wind	Mod. Ratio
Small	Upwind	Older	Slow	0.5675
Small	Upwind	Older	Fast	0.6678
Small	Upwind	Same	Slow	0.0758
Small	Upwind	Same	Fast	0.1116
Small	Upwind	Younger	Slow	0.3962
Small	Upwind	Younger	Fast	0.5013
Small	Downwind	Older	Slow	0.5216
Small	Downwind	Older	Fast	0.6694
Small	Downwind	Same	Slow	0.0638
Small	Downwind	Same	Fast	0.1123
Small	Downwind	Younger	Slow	0.3528
Small	Downwind	Younger	Fast	0.5030
Large	Upwind	Older	Slow	0.7887
Large	Upwind	Older	Fast	0.7912
Large	Upwind	Same	Slow	0.1891
Large	Upwind	Same	Fast	0.1915
Large	Upwind	Younger	Slow	0.6511
Large	Upwind	Younger	Fast	0.6545
Large	Downwind	Older	Slow	0.7481
Large	Downwind	Older	Fast	0.8687
Large	Downwind	Same	Slow	0.1566
Large	Downwind	Same	Fast	0.2926
Large	Downwind	Younger	Slow	0.5976
Large	Downwind	Younger	Fast	0.7679

When the central planting is either old or young compared to outside plantings, the catch modification ratio should be larger than when outside plantings are the same age. This is because if there is a large difference in planting ages, the outside plantings will be in relatively unattractive stages for earworm during the period when modified trap catches are being calculated and summed (when the central planting is tasselling). The net effect of this should be that the contribution-to-catch levels for each pixel in outside planting locations will be lower. The proportion of total contribution to catch values coming from the center planting then will be higher. For example, the SUSS (Small planting, Upwind trap, Same age, Slow wind) combination produced a trap modification ratio of 0.0758, while SUOS (older central planting) produced 0.5675 and SUYS (younger central planting) produced 0.3962.

The affect that trap location has on the trap catch modification ratio will depend in part on wind speed. As figures 11 and 12 show, fast winds tend to increase the likeliness of catch values for positions obliquely upwind of the trap. If the trap is on the downwind side of the planting, then these raised values are more likely to occur on locations within the central planting. Therefore the trap modification ratio should be higher on fields with high winds and downwind traps than they are for fields with high winds and upwind traps. This affect is likely to be more pronounced when the central planting is large. As an example, the LUOF (Large planting, Upwind trap, Older central planting, Fast wind) combination produced a trap modification ratio of 0.7912, while the LDOF (Downwind trap) produced 0.8687. The difference is less apparent between SUOF, where the trap modification ratio is 0.6678, and SDOF, where the ratio is 0.6694.

This sensitivity exercise indicated that the model was responsive to changes in spatial conditions and did function as expected. The model was sensitive to changes in input conditions with trap modification ratios ranging from 0.0638 to 0.8687. With this assurance that the model functioned reasonably well with hypothetical situations, it was then tested against real field situations.

### Testing the Simulation Model: Actual Site Data

As a further test of the model, a single-day run was done for actual field locations to see what kind of catch modification ratios were produced. Three locations were selected to represent three extremes of conditions: an isolated planting, a planting with large amounts of same-age corn growing nearby, and a planting with little same-age corn but with large amounts of younger or older corn. Same-age is defined as any planting which at some point is silking at the same time as the trapped planting. Data from 1990 were used for this analysis and the day used was August 10, 1990. This day was chosen because it was the day when the greatest number of plantings were tasseling and therefore would allow for the greatest choice of sites to compare. The three sites chosen were Schlegel, Meyer2, and Greenville2. Maps of these sites can be found in Appendix A. Schlegel represents an isolated planting since no corn other than the trapped planting was within one kilometer of the pheromone trap. The mean evening wind speed at Schlegel on August 10 was determined by the AFWIND program to be 123 meters/minute and the mean wind direction was 307° (from the NW). Meyer2 represents a planting surrounded by large amounts of same-age corn since it had the largest amount of same-age corn (85.2 hectares). The mean evening wind speed at Meyer2 was determined to be 79 meters/minute and the mean wind direction was 302° (from the NW). Greenville2, with no same age corn growing within 1 kilometer of the trap and 39.9 hectares of different aged corn, was used for the third location. The mean evening wind speed at Greenville2 was determined to be 32 meters/minute and the mean wind direction was 288° (mostly from the West).

The sensitivity of the model to errors in input data and changes in model parameters was tested by running the model with these changes. Two data values input into the model (wind speed and direction) were altered by the addition or subtraction of errors. Errors considered for wind speed were: -60 m./min., -10 m./min., 0, +10 m./min., and +60m./min. Errors run for wind direction included: -90°, -10°, 0, +10°, and +90°. Three model parameters were also altered to see how the model would respond: pheromone plume length, moth search time, and moth search angle (a crosswind moth search pattern is used for all runs). Pheromone plume length values tested were 25, 75, and 200 meters. Moth search times tested were 5, 30, 60, and 540 minutes. Moth search angles tested were 10°, 45°, and



90°. Though cross interactions were possible for the 2 altered input data values and 3 altered model parameters, no attempt was made to account for model response to all 675 combinations of alterations. Instead, each was tested separately. Standard values were assigned to data values and parameters not being tested, and the tested data value or parameter was then altered. Standard values of 75 meters for plume length, 30 minutes for moth search time, and 45° for moth search angle were used. The standard for wind speed and direction was to assume no added error.

All of the variations described in the above paragraphs affect model response by changing the likeliness of capture map surface. As already noted, increasing wind speed results in higher likeliness of catch values for locations obliquely upwind of the pheromone trap (Figures 11 and 12). Figures 20a and 20b show the effect of altering plume length. Increasing plume length results in a broadening of the areas with high likeliness of capture. Figures 21a and 21b show the affect of altering moth search time. From these figures we can see that a change from 16 minutes to 540 minutes only resulted in a slight brightening and a broadening outward of the likeliness of catch image. Figures 22a and 22b show the effect of altering search angle. From these figures we can see that broadening the angle also results in a dilution of likeliness to capture and that the lighted area does not go as far out.

Table 8 shows the response of the model for different error levels with wind speed. As was observed in the hypothetical corn planting section (above), isolated plantings did not have their trap catch altered. Non-isolated planting's trap catch values were altered by differing amounts depending on how close to the age of the trapped planting the outside plantings were. Same-age nearby plantings resulted in the greatest modification to trap catch. Schlegel, an isolated planting, was unaffected by changes in wind speed. When a wind speed error of 60 was added to the Schlegel site, wind speed became faster than moth speed (180 meters/minute) and moth flight activity was assumed by the model to stop. For Meyer2, as wind speed increased the trap modification ratio increased. This implies that at higher wind speeds a greater proportion of the trap catch came from within the trapped planting. Since the trap was placed on the southwest corner of this planting and most of the planting is obliquely upwind of the trap, a change which places more emphasis on obliquely upwind locations (such as an increase in wind speed) is likely to increase the influence of the trapped planting. Greenvilla2 also had its trap modification ratio increase as wind speed increased. This is probably due to a reduction in the influence of the closest older planting northeast of the trap. This

planting is crosswind to the trap so that as wind speeds increase, the high likeliness of catch areas move obliquely upwind and away from it.

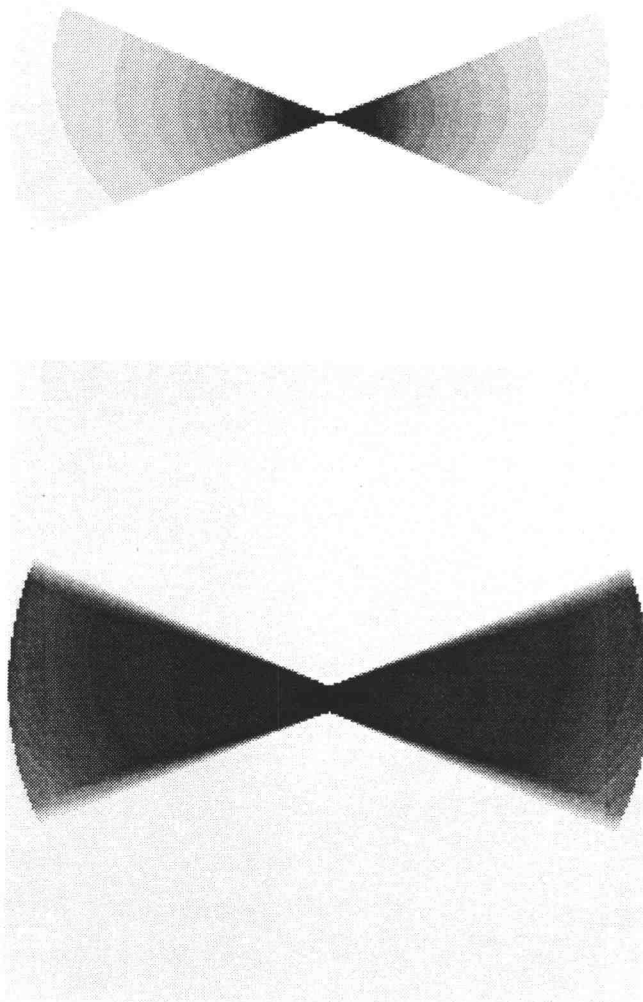


Figure 20. Image of the "Likeliness of Capture" Map Layer. For this image a 100 meter/minute wind is blowing from the top side, a cross-wind search angle of  $45^\circ$  was used, and a search time of 30 minutes was used. Figures "a" and "b" show the surface when plume active space lengths of 25 and 200 meters are used. Likeliness of capture is indicated by shading with dark locations having a relatively high likeliness of capture and light areas having a low likeliness of capture. The pheromone source is located on the top side of the white region in the center of the image.

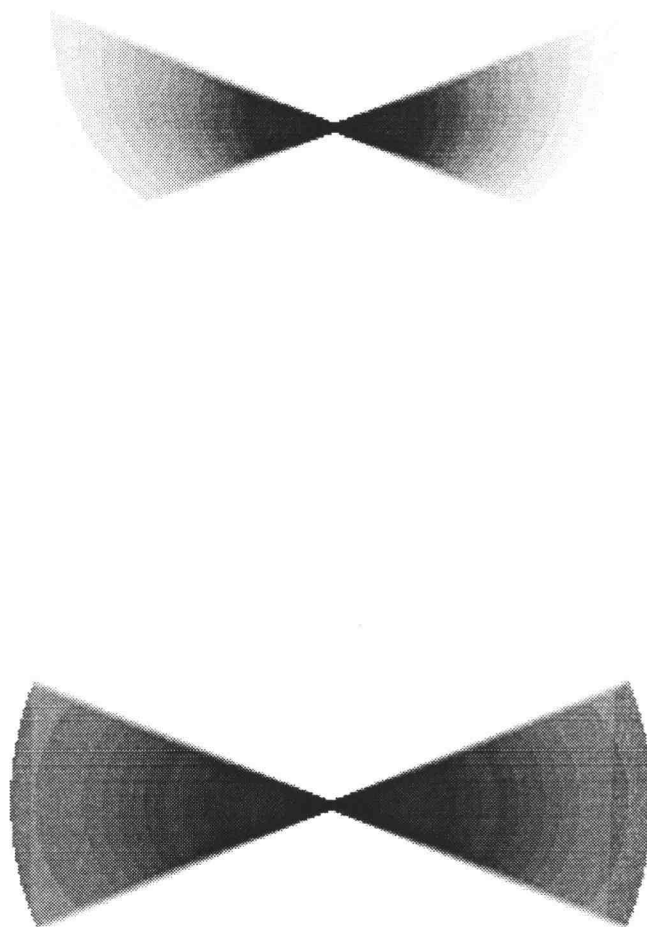


Figure 21. Image of the "Likeliness of Capture" Map Layer. For this image a 100 meter/minute wind is blowing from the top side, a cross-wind search angle of  $45^\circ$  was used, and a plume active space length of 75 meters was used. Figures "a" and "b" show the surface when a search time of 16 and 540 minutes are used. Likeliness of capture is indicated by shading with dark locations having a relatively high likeliness of capture and light areas having a low likeliness of capture. The pheromone source is located on the top side of the white region in the center of the image.

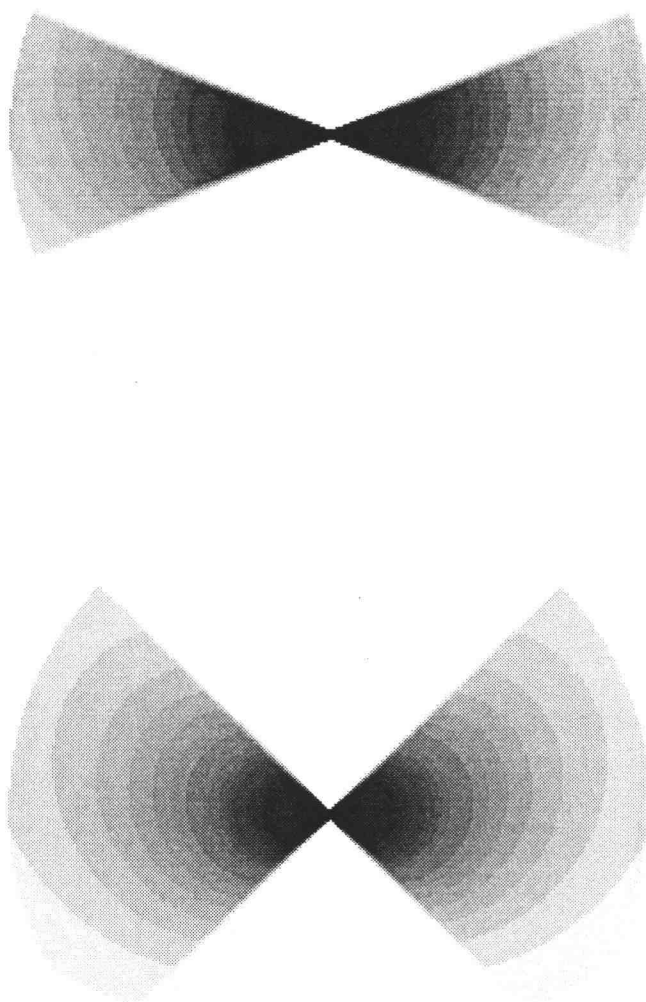


Figure 22. Image of the "Likeliness of Capture" Map Layer. For this image a 100 meter/minute wind is blowing from the top side, a search time of 30 minutes was used, and a plume active space length of 75 meters was used. Figures "a" and "b" show the surface when search angles of  $45^\circ$  and  $90^\circ$  are used. Likeliness of capture is indicated by shading with dark locations having a relatively high likeliness of capture and light areas having a low likeliness of capture. The pheromone source is located on the top side of the white region in the center of the image.

Table 8. Trap catch modification values resulting from adding errors to wind speed. The model was run for August 10, 1990 on three sites representing an isolated site, a site surrounded by large amounts of same-age corn, and a site surrounded by large amounts of different age corn. For each of these sites wind speed was altered by the addition of errors (-60, -10, 0, +10, +60 meters/minute). For these runs of the model a pheromone plume active space length of 75 meters, a moth search time of 30 minutes, and a moth search angle of 45° were used.

Site\WindSpeed (WS) Error	WS - 60	WS -10	No Error	WS+10	WS+60
Isolated (Schlegel)	1.0000	1.0000	1.00000	1.00000	NA
Surr. by same-age corn (Meyer2)	0.3009	0.3031	0.30391	0.30501	0.31799
Surr. by diff. age corn (Greenville2)	0.5326	0.5340	0.53511	0.53651	0.55135

Table 9 shows trap modification ratios for runs of the model as wind direction errors are added to the model. This table shows that wind direction errors can have drastic effects on the trap modification ratio, and that those effects can only be determined by examining the map. For example, Schlegel has its trap modification ratio drop down to 0.3 when an error of -90° is added to wind direction even though it is a relatively isolated planting. A -90° modification to wind direction results in a southwest wind rather than a northwest wind. This moves the "beam" of locations with a high likeliness of capture directly across those same-age plantings northwest of the trap. A +90° modification causes the wind to come from the northeast. The beam of locations with a high likeliness of capture moves somewhat in the direction of those other plantings, but since it is angled obliquely upwind it doesn't cross them as directly. The net result is that a +90° error also decreases the catch modification ratio, but not by as much as the -90° modification. For Meyer2 a wind direction error of -90° results in a southwest wind. Though the plume is now blowing directly across the trapped planting, the beam of high likeliness of catch locations is directly over a couple of large same-age plantings (the

planting directly northwest of the trap). The influence of the trapped planting is somewhat reduced. When a  $+90^\circ$  error is added to the wind it comes from the northeast. Now not only does the sideways beam still cross over those same-age plantings, but the trapped planting is entirely upwind of the trap and within the upwind "shadow". For Greenville2, the outside plantings which have maximum influence on determining the catch modification ratio are located north and south of the trap. Since the wind originally came from the west a change of plus or minus  $90^\circ$  which moves the wind to the south or the north will result in both outside plantings falling within the upwind and downwind "shadows" of the likelihood of catch surface. Therefore such large alterations in wind direction will increase the influence of the trapped planting and increase the catch modification ratio.

Table 9. Trap catch modification values resulting from adding errors to wind direction. The model was run for August 10, 1990 on three sites representing an isolated site, a site surrounded by large amounts of same-age corn, and a site surrounded by large amounts of different age corn. For each of these sites wind speed was altered by the addition of errors ( $-90^\circ$ ,  $-10^\circ$ ,  $0^\circ$ ,  $+10^\circ$ ,  $+60^\circ$ ). For these runs of the model a pheromone plume active space length of 75 meters, a moth search time of 30 minutes, and a moth search angle of  $45^\circ$  were used.

Site\Wind Direction Error	WD- $90^\circ$	WD- $10^\circ$	No Error	WD+ $10^\circ$	WD+ $90^\circ$
Isolated (Schlegel)	0.33337	1.0000	1.0000	0.99547	0.79191
Surr. by same-age corn (Meyer2)	0.11124	0.35238	0.3039 1	0.25340	0.00046
Surr. by diff. age corn (Greenville2)	0.98631	0.50360	0.5351 1	0.61652	0.91803

Table 10 shows trap modification values when three different plume active space lengths are used on the three test locations. Again, it can be seen that the result of an alteration depends on the locations, shapes, and ages of corn plantings around the pheromone trap. For Meyer2, increasing the plume length results in a decrease in the influence of the trapped planting on trap catch. For Greenville2 such an increase has the opposite effect. Schlegel, the isolated site, is unaffected by plume length. Meyer2, with its NW wind, has a plume that blows obliquely away from the trapped planting. Increasing the plume length increases the area within the corn plantings southwest of the trap that fall within the area of high likelihood of catch. Greenville 2 has a westerly wind that blows straight into the trapped planting. Broadening the beam of highly likely catch locations results in an increase in overlap for the area of high likelihood of catch and the trapped planting. The planting south of the trap also overlaps more with the area of high likelihood of catch, but not as much as the trapped planting.

Table 10. Trap catch modification values resulting from using different lengths of active space for the pheromone plume. The model was run for August 10, 1990 on three sites representing an isolated site, a site surrounded by large amounts of same-age corn, and a site surrounded by large amounts of different age corn. For these runs of the model a moth search time of 30 minutes and a moth search angle of 45° were used.

Site\Plume Length (PL)	PL=25 meters	PL=75 meters	PL=200 meters
Isolated (Schlegel)	1.000000	1.000000	1.000000
Surr. by same-age corn (Meyer2)	0.345587	0.303914	0.195525
Surr. by diff. age corn (Greenville2)	0.534367	0.535114	0.564520

Table 11 shows the results of increasing the moth search time. Except for Schlegel, increases in search time consistently resulted in reductions in the influence of the trapped planting on the moth catch. It seems intuitive that increasing the moth search time results in locations farther away from the trap getting assigned higher likelihood of catch values. Though it would probably be possible to construct a particular pattern of plantings that would result in an increase in the influence of the trapped planting as a result of increasing the search time, in general the net effect of increasing search time will probably be a reduction in influence for the trapped planting.

Table 11. Trap catch modification values resulting from using different search times (measured in minutes). The model was run for August 10, 1990 on three sites representing an isolated site, a site surrounded by large amounts of same-age corn, and a site surrounded by large amounts of different age corn. For these runs of the model a pheromone plume active space length of 75 meters and a moth search angle of 45° were used.

Site\Moth Search Time (ST)	ST=5	ST=30	ST=60	ST=540
Isolated (Schlegel)	1.000000	1.000000	1.000000	1.000000
Surr. by same-age corn (Meyer2)	0.539222	0.303914	0.291353	0.281354
Surr. by diff. age corn (Greenville2)	0.912093	0.535114	0.496786	0.468389

Table 12 shows the effect of altering the moth search angle. The effect of altering search angle varies and depends on locations, shapes, and timings of plantings around the trap. If there are large acreages of corn crosswind to the trap, a more concentrated crosswind searching pattern results in a decrease in the influence of the trapped planting on the ultimate trap catch. If there are large acreages of corn in upwind-downwind directions then a concentrated crosswind searching pattern



increases the influence of the trapped planting. If the trapped planting itself has large areas crosswind to the trap, then a concentrated cross-wind search pattern increases its influence on trap catch. For example, Schlegel has relatively few plantings crosswind (NE or SW) to the trap and a large number of plantings upwind of the trap. When search angle is increased, those upwind plantings fall into the region of high-catch-likeliness and as a result the catch modification ratio decreases. Greenville2 has one planting crosswind to the trap and within 100 meters. An increase in searching angle decreases the influence of this crosswind planting by including large acreage's of the trapped planting which are to be found more downwind of the trap. It isn't easy to visually interpret the situation at Meyer2, but apparently increasing the cross angle search pattern resulted in more areas from within the trapped planting falling into the area of high likeliness of catch than for areas from outside plantings.

Table 12. Trap catch modification values resulting from using different moth search angles. The model was run for August 10, 1990 on three sites representing an isolated site, a site surrounded by large amounts of same-age corn, and a site surrounded by large amounts of different age corn. For these runs of the model a pheromone plume active space length of 75 meters and a moth search time of 30 minutes were used.

Site\Search Angle (SA)	SA=10°	SA=45°	SA=90°
Isolated (Schlegel)	1.000000	1.000000	0.960046
Surr. by same-age corn (Meyer2)	0.265761	0.303914	0.311009
Surr. by diff. age corn (Greenville2)	0.364675	0.535114	0.705041

### Simulation Model Results

A one variable regression model between cumulative trap catch (1st tassel to 1st silk) and damage (using the same transformations used in the multiple regression model) proved to be significant ( $P=0.000$ , 1990;  $P=0.005$ , 1991) and had an  $R^2$  of 0.64 for 1990 data and 0.29 for 1991 data. The model was intended to modify trap catch values so as to produce a higher correlation with damage levels. As has already been observed, built into the model are options for making many changes that could seriously alter its behavior. In addition to alterations in search time and plume length, the model can be altered so as to assume 1) that moths search for plumes in a cross-wind search pattern, 2) that corn age is or is not an important consideration, and 3) that corn plantings blocked from the trap by a wind blocking feature not be considered by the model. When cross-wind searching patterns are used, the allowed angle of crosswind search is an additional parameter that can be changed. To run the model for all combinations of these model alterations as well as possible combinations of parameter values would require many thousands of runs of the model. The model loaded the central processing unit of our computer severely and only two runs of the model could be accomplished per day. Because of this, the amount of alternative models that could be tested was severely limited. Therefore a limited subset of possible models was investigated. Four runs were done for all combinations of the three structural alterations to the model listed above. Those four runs were for 4 combinations of search time and plume length. A 75 meter wind plume was used for long-plume runs and a 25 meter plume was used for short-plume runs. A 540 minute (9 hours) search time was used for long search time runs and a 16 minute search time was used for short search time runs. For each of these runs the  $R^2$  between modified trap catch and damage was recorded and is listed in Table 13 below.

Seldom did any run of the model result in  $R^2$  values higher than what was observed for unmodified trap catch (0.6393) and none of the model runs had  $R^2$  values that were significantly higher. All of the 8 runs with higher  $R^2$  values were cases where corn age was not used to produce different moth concentration levels. This is in agreement with the results from the regression model where considering corn age also did not improve model performance. Acreage's of all corn within 2.0 kilometers proved to be the most significant input variable from among all the possible corn-acreage input variables. Those that differentiated between corn ages

proved to be less significant. The 8 runs with higher  $R^2$  values also were cases where corn blocked from a line of sight to the pheromone trap by wind blocking features were excluded from consideration. There was a general tendency for  $R^2$  values to be higher when the model assumed cross wind search patterns for moths not in contact with a pheromone plume. All else being the same,  $R^2$  values were consistently higher for 25 meter pheromone plumes than they were for 75 meter plumes. Of the 16 pairs of runs where all else was equal except for differences in search time, the runs with a 540 minute search time resulted in higher  $R^2$  values 12 times.

Table 13.  $R^2$  values observed for altered versions of the model. Alterations included are: 1) Setting likely moth densities within plantings to be a function of planting stage for any date versus assuming moth density is the same for all corn plantings regardless of age, 2) including corn plantings hidden from view to the trap by wind blocking features versus excluding them, 3) assuming a cross-wind searching pattern for moths not in contact with a pheromone plume versus assuming a random search pattern, 4) a long plume length (75 meters) versus a short one (25 meters), and 5) a long search time (540 minutes) versus a short search time (16 minutes). When cross-wind search is used the allowed angle for cross-wind search is set to  $45^\circ$ . An asterisk is used to mark all combinations that resulted in an  $R^2$  higher than for unmodified trap catches.

1) Consider Corn Age	2) Only consider unblocked corn	3) Assume Cross-Wind Search	4) Plume Length (meters)	5) Search Time (minutes)	Resulting $R^2$
Y	Y	Y	75	16	0.6143
Y	Y	Y	75	540	0.6145
Y	Y	Y	25	540	0.6228
Y	Y	Y	25	16	0.6231
Y	Y	N	75	16	0.6115
Y	Y	N	75	540	0.6129
Y	Y	N	25	540	0.6174

Table 13. (Continued.)

1) Consider Corn Age	2) Only consider unblocked corn	3) Assume Cross-Wind Search	4) Plume Length (meters)	5) Search Time (minutes)	Resulting R <sup>2</sup>
Y	Y	N	25	16	0.6167
Y	N	Y	75	16	0.6085
Y	N	Y	75	540	0.6095
Y	N	Y	25	540	0.6162
Y	N	Y	25	16	0.6143
Y	N	N	75	16	0.6015
Y	N	N	75	540	0.5889
Y	N	N	25	540	0.6080
Y	N	N	25	16	0.6039
N	Y	Y	75	16	
N	Y	Y	75	540	0.6426*
N	Y	Y	25	540	0.6517*
N	Y	Y	25	16	0.6515*
N	Y	N	75	16	0.6428*
N	Y	N	75	540	0.6428*
N	Y	N	25	540	0.6501*
N	Y	N	25	16	0.6467*
N	N	Y	75	16	0.6372
N	N	Y	75	540	0.6362
N	N	Y	25	540	0.6477
N	N	Y	25	16	0.6461
N	N	N	75	16	0.6271
N	N	N	75	540	0.6116
N	N	N	25	540	0.6359
N	N	N	25	16	0.6339

## 5. Discussion

### Observed Trap Catch and Damage Levels

It is curious that damage levels in 1990 and 1991 were so unusually low compared with 1988 - 1989 (Figure 18), but that peaks of daily trap catch averages don't reflect such low levels (Figure 17). In fact the peak value for average daily trap catch in 1991 exceeded the peak value observed in 1989. One possible explanation may lie in the relative timing of moth flights versus corn phenology from year to year. Figures 23a-23d show silking timings for monitored fields versus trap catch values. Each bar represents the number of monitored sites that were silking during that 3-day time period. Lines show average trap catch values per trap-day. From these graphs, a possible explanation for the unusually low damage levels observed in 1991 can be found. In 1988, moth flight was not especially well synchronized with silking. Corn fields started silking a little ahead of the moth flight. Damage still was relatively high because moths were especially numerous during that peak flight period. In 1989, moth flight levels were extremely low (the lowest observed in this four-year period), but they were well synchronized with the timing of corn silking. The net result of this were relatively moderate damage levels. In 1990 the distribution of number of silking sites is bimodal. This is probably a reflection of a bias towards selecting early and late plantings to monitor. Whether the bimodal distribution represents actual valley-wide conditions or a sampling bias, moth flight still does not seem to be well synchronized with the silking of corn. The relatively moderate damage levels observed in 1990 probably results from the fact that moths were numerous during the peak flight periods. The first three weeks of August, average moth flight levels were the highest observed over these four years. From the last week of August until the end of September, moth flight levels in 1990 were the second highest observed. In 1991 moth flight levels were both low and very poorly synchronized with the silking of corn. The net result of this poor synchrony is a year with unusually low damage levels.

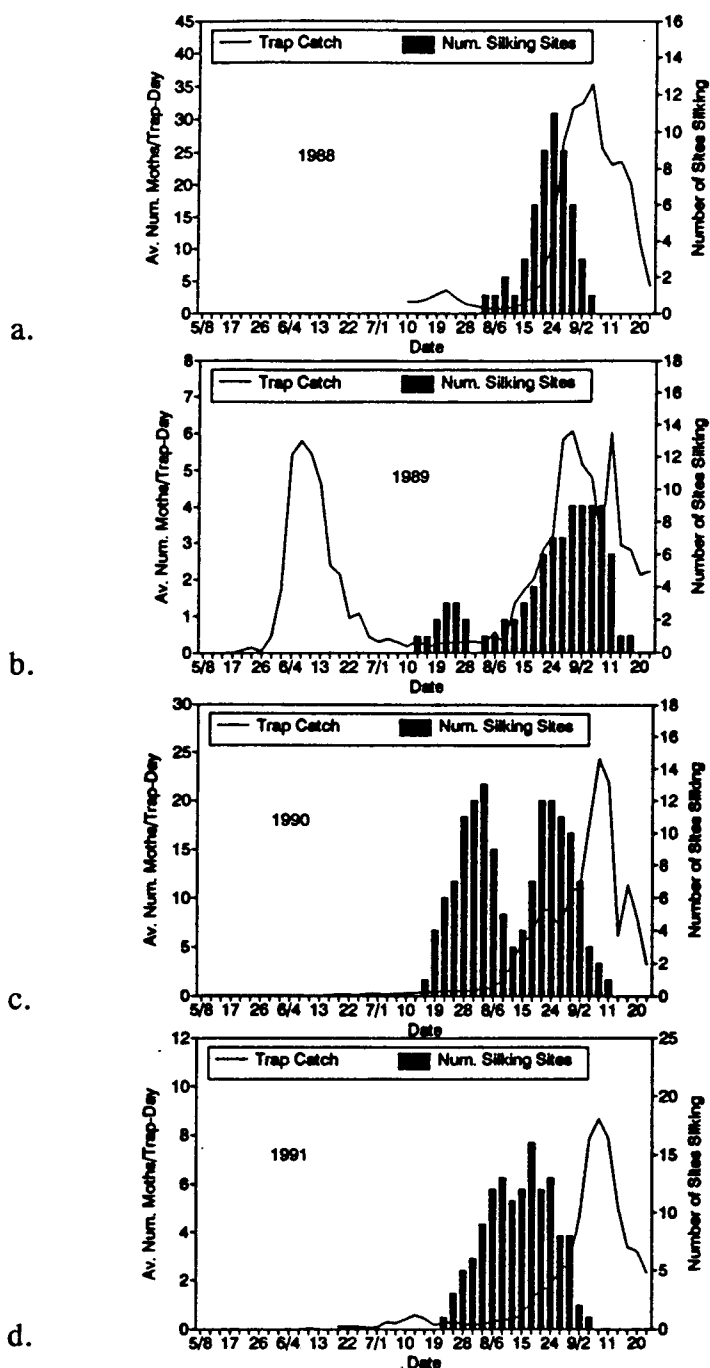


Figure 23. Comparisons of the timing of peak moth flights versus the timing of corn silking. Histogram bars represent the number of sites from among the monitored sites that were in silking stage during that time period. The line represents the average moth catch per site-day observed from all traps. Figures a-d shows results from 1988-1991.

### Multiple Regression Model

The optimal multiple regression model obtained from 1990 data included four input variables: Date of 1st silk, the number of hectares of corn within two kilometers of the trap, the average distance on the north side of the trap to wind blocking features, and cumulative trap catch. Date of 1st silk had a positive regression coefficient. This means that corn plantings that silk later in the season can be expected to have higher damage levels. This is partially explained by the relative timings of silking versus moth flight observed in Figure 21. Moth flights tended to be a little later than corn silking dates. For all four years, the earliest plantings silked before the main moth flight period began. For all four years, late plantings silked well within the period of peak moth flights. The positive regression coefficient for trap catch also fits well with patterns already discussed. High trap catches imply large moth populations. Oviposition levels and subsequent damage should be high as well. The positive relationship observed here is in concurrence with previous observations (Chowdhury et al., 1987; Coop et al. , 1992).

The most intuitive expectation would be that larger acreages of corn would result in an increase in the expected damage level. The expectation would be that large amounts of corn planted in any one location would cause migrating moths to preferentially land there and increase the local moth population. However, this is not the result that actually occurred. Instead, there was a negative regression coefficient for corn area. Larger local acreage's of corn result in lowered estimates of damage. A possible explanation for this observation is that those large acreages of corn outside of the trapped planting will have their own moth populations and that males from these populations will be drawn to the pheromone trap. The net result of this will be that the pheromone moth catch will be artificially increased as a result of an influx of moths from outside plantings. In order to come up with a more accurate prediction of damage levels within the trapped planting, damage prediction value will have to be lowered.

The reason for a negative regression coefficient for the average distance to north wind blocking features is also not readily apparent. This negative coefficient says that the farther away from the trap north wind blocking features are, the lower you should make your damage prediction. This can be stated conversely that the closer to your trap these features are, the higher you should make your damage prediction. The most likely explanation for this is that wind blocking features

interfere with the normal movement of the plume. Winds came predominantly from the north. Therefore wind blocking features on the north side will probably have the most disruptive effect on the pheromone plume. A disrupted plume results in a lower trap catch. Therefore, the damage prediction needs to be raised if it is to be accurate.

In 1991 only the date of 1st silk proved to be significant as an input variable for prediction of percent infestation. Again, the regression coefficient for date of 1st silk proved to be positive. That trap catch and none of the potential spatial input parameters proved significant in 1991 does not necessarily invalidate them as useful data. Earworm damage levels were unusually low in 1991. Though the correlation between trap catch and damage levels for individual sites was low, the generally low trap catch levels observed for all sites did accurately reflect the low damage levels observed valley-wide. Anyone using pheromone traps in 1991 to monitor for earworms would have correctly determined that earworms would not be a problem that year. When damage levels are so low, normal variation probably washes out all but the strongest trends. More observations from moderate to high damage years will be needed before any final evaluation can be made on the reliability of corn area and distance to wind blocking features as damage prediction modifying parameters.

### Simulation Model Results

Unfortunately, earworm moth populations were very low during the two field seasons for which the field evaluation component of the thesis was funded. Coop et al. (1992) determined an economic injury level of 27% infestation for processed sweet corn in the Willamette Valley. This is the level of infestation at which pesticide applications become marginally cost effective. As can be seen in the scatter plots of Figure 18, only one site sustained infestation levels of that magnitude over 1990 and 1991. The majority of sites sustained damage levels of less than 10%. Infestation levels were too low to allow the model much discriminatory power. When the infestation levels for most sites range from 0 to 10% a damage prediction model with an error of +/- 5% will not appear to be very successful. The same model run in a year with damage ranging from 0 to 90% may look very successful.



A true test of the simulation model will only occur when data is collected from a year with such a range of damage levels. Since I am constrained by the years from which data was collected, I can only infer that the model is an accurate representation. Already I have shown that the behavior of the model for a single site and a single day is logical and internally consistent. This was done in the results section for both hypothetical and actual site data. Now I would like to demonstrate that the model behaved well over aggregate runs over many days for many sites. Data from 1990 will be used since this year had the higher damage levels and the greater chance of producing meaningful results. In this section I will first look at how the model behaved for four locations that were outliers in the scatter plots of unmodified cumulative trap catch versus subsequent damage. Second I will look at how the model behaved at the two sites with highest damage levels.

Figures 24a-c show a before modification scatterplot, a scatterplot with arrows denoting modifications made by the model, and an after-modification scatterplot. Four particularly large outlier locations are labeled. Three of the outliers (Schlegel, Meyer2, and Greenville2) were situations where the amount of damage observed was unusually low given the number of moths captured. The fourth outlier (Jones) was a situation where the amount of damage observed was unusually high given the number of moths captured. Since the model functions by lowering trap catches for sites, the affect that the model has on the scatterplot of trap catch versus damage is to move points leftward. It was hoped that points such as Schlegel, Meyer2, and Greenville2 would be moved relatively long distances leftward and that points such as Jones would be moved very little. If the model were to functioned in this manner, it would improve the correlation between trap catch and damage.

From Figures 24a-c it can be seen that the model actually seems to have worked reasonably well for three out of the four selected points. Jones, which should have moved very little, did end up moving very little. Note though, that Jones still is an outlier after modification. Meyer2 should have moved substantially and did so, though it moved a little too far. Greenville2 moved about the right distance to place it directly between the highest damage point and the clump of relatively low damage level sites. The only site of these four which fared poorly with the model was Schlegel, which should have moved substantially but didn't. After modifications, Schlegel still exists as an outlier.

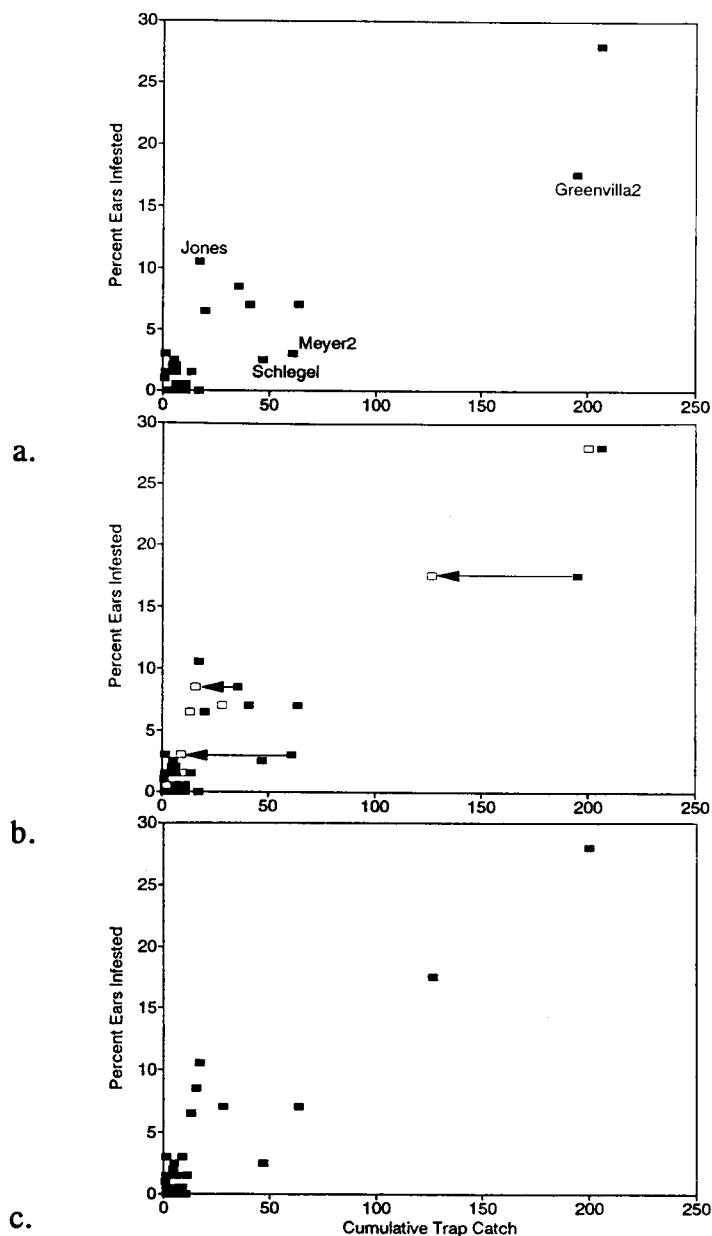


Figure 24. a) Scatterplot of cumulative pheromone trap catch from 1st tassel to 1st silk versus subsequent damage (% infestation) for unmodified trap catch in 1991. b) Modifications made to catch levels by a run of the model. Solid squares represent before-modification values and open squares represent after-modification values. Where movement was too small to detect only a black square is visible. Where movement was relatively short, open and filled square pairs will be next to each other (with the open square always to the left). Where movement was large, an arrow is placed to indicate open and closed square pairs. c) Same scatterplot after modification of trap catch.

As was observed with the hypothetical corn plantings (see Table 7), the model reduces trap catch by larger amounts when the trapped planting is surrounded by other corn fields of nearly the same age. Isolated corn fields and corn fields that are surrounded by corn that is much younger or older will have their trap catch values modified very little. Of the four plantings labeled in Figures 23a-c, two were modified very little. Jones was a planting for which little modification was desirable and was a rather isolated planting bordered on the west by a slightly older planting (maps of all plantings can be found in Appendix A). At the time the trapped planting started to tassel, the adjacent planting was close to silking. This means it potentially could have been a major source of moths for the trap to catch and therefore could potentially have caused the model to modify trap catch with a large reduction. The reason it didn't probably has to do with wind direction. Out of the nine days between first tassel and first silk, the wind came predominantly out of the northwest eight days and out of the west on the remaining day. As a result of this, the western planting of corn always was to be found in areas with low contribution to catch values (Figures 11 and 12). Schlegel was a site for which a large reduction in trap catch would have been desirable, but it is an isolated planting and was left relatively unmodified by the model.

Of the four plantings labeled in Figures 23a-c, 2 were modified to a considerable extent. In both of these cases the modification was beneficial and increased the correlation between trap catch and damage. Greenville2 had a moderately large planting positioned less than 100 meters downwind of the pheromone trap. Though this planting was considerable older than the trapped plantings and was a poor source for additional male moths to the trap, it produced a large adjustment as a result of its close proximity to the trap and the large area of overlap between its boundaries and those areas of high likeliness of catch. Meyer2 was bordered both on the east and the west by plantings relatively close in age. At the time that the trapped planting was starting to tassel, the east planting was in mid tassel stage and the west was close to silking. Moth activity in both of these plantings no doubt was very high at this time and both sites contributed significant numbers of moths to the trap catch. The modification model, in filtering out these extra moths, reduced the moth count considerably.

In 1990 there was only one site that sustained even marginally economic levels of damage. One cannot assess the model impact for the scatter plot of a single point, so I looked at how the two locations with highest damage levels observed in 1990 fared in relation to the clump of points with extremely low damage levels. (Note: The second highest point, Greenville2, was also an outlier in the scatter plot of unmodified catch versus damage and has already been discussed.) These upper two points are very influential in producing the relatively high  $R^2$  values observed in 1990. Had these two sites not been monitored in 1990, then the scatter plot of trap catch versus damage for 1990 would have been as poor as was observed in 1991. If 1990 could be viewed as a year with essentially three points, the top two plus the centroid of the clump of bottom points (Figure 25), then the model would appear to have behaved very well. Before modification the middle point (Greenville2) was too far to the right to produce a strong correlation. After modification, the top site moved very little and the middle site moved to place itself between the top point and the centroid of low points.

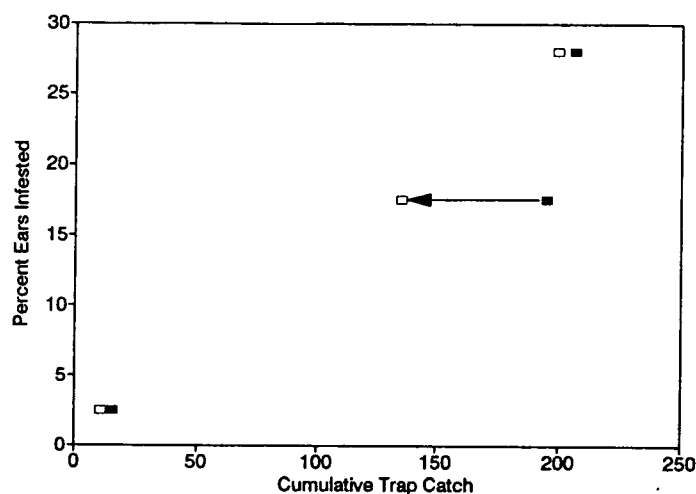


Figure 25. The scatterplot of trap catch versus damage for unmodified and modified trap catches when the bottom 27 locations are combined into a single centroid. Filled squares show unmodified catch versus damage values; open squares show modified catch versus damage values. The arrow marks the movement of the center point.

### The Simulation Model: Questions on Accuracy of Wind and Damage Estimates

Questions could be raised as to the accuracy of some of the measured and estimated input values used in this model. For instance, use of the AFWIND wind interpolation model to produce wind vector values for each site could have been inaccurate. A phone conversation with the programmer of AFWIND revealed that he suspected that the program was conservative in its estimations of the impacts of topographic features. i.e. that a large hill produced less disturbance in AFWIND's wind field than an actual hill would (Kunkel, personal communication). Other sources of input data errors include errors in the damage estimates taken for each site. Whether 200 ears were large enough samples to accurately estimate damage levels in corn fields can be questioned. Whether the sampling methods used to obtain those 200 ear samples was near random enough for unbiased estimates of damage can also be questioned.

As was outlined in the Materials and Methods section, wind vectors for each site are determined using interpolations between wind stations at three airports. Any interpolation method will produce some errors. To test to see if the AFWIND model produced significant errors, I ran the AFWIND model with data from one of the three sites removed. The wind field generated by the model produced a wind vector for the missing site and this could then be compared with the actual wind data. This process was repeated for every day in the 1990 season for which data was available from all three airport locations. The method of choosing an airport for removal was sequential. i.e. Salem would be removed one day, Corvallis would be removed the next, then Eugene, etc. Observed wind vectors were subtracted from predicted wind vectors to produce difference vectors. A total of 29 such wind difference vectors were produced. Hotelling's One Sample Test (p.144 in Batschelet, 1981) was then used to determine if the average difference vector was significantly different from zero. The results of this test (Table 14) was a failure to reject the hypothesis that the error vector is a zero vector ( $\alpha=0.05$ ). Therefore this test was not able to show that the wind vectors output by AFWIND were significantly different from true wind values.

Table 14. Results of a Hotelling's One Sample Test conducted on wind difference vectors which were created by subtracting observed wind vectors from wind vectors predicted by AFWIND. A total of 29 such wind difference vectors were used.

$H_0$ : Mean Vector = 0 $n=29$ Test Statistic $T^2 = 4.1076$ $T^2_{(0.05)} = 2(n-1)/(n-2) F_{2,n-2}(0.05) = 6.948$ If $T^2 > T^2_{(0.05)}$ we reject $H_0$ Result: $4.1076 < 6.948$ therefore we cannot reject $H_0$
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Had more time been available, a study of ear damage levels across a field would have provided valuable information on how to optimally sample. The damage sampling methods employed here were the best possible given a shortage of sampling time and a lack of information on damage distributions and variance levels. One method for estimating the suitability of the 200 ear sample size is to use the confidence interval for proportional estimates as described in Bhattacharyya and Johnson (1977). They cite a method using a normal approximation for calculating the confidence interval of a binomial parameter  $p$ . This confidence interval is  $p \pm z_{\alpha/2} \sqrt{p(1-p)/n}$ . Damage samples from this study essentially are estimates of a binomial parameter since each sampled ear is determined as being in one of two states, infested by earworms or not. The equation cited above produces confidence intervals that are relatively narrow when the estimated  $p$  value is close to 0.0 or 1.0, and are relatively wide when the estimated  $p$  value is near 0.5. Table 15 shows examples of calculated confidence intervals for different  $p$  values when  $\alpha$  is set equal to 0.05 and a sample size of  $n=200$  is used. As can be seen from this table, the confidence interval ranges from 0.01 for  $p$  values of 0.01 on up to values of 0.07 for  $p$  values of 0.5. Note that a confidence interval of 0.07 translates to a change of 7%. Considering these potential errors and looking at the scatterplots in figure 18 of cumulative catch versus percent corn ears infested it can be seen that for years such as 1989 and 1990, where the linear relationship between trap catch and damage is strongest, changes to percent infestation of the magnitudes shown in the confidence intervals could potentially tighten up the correlation between trap catch

and damage. For 1988 and 1991, the scatterplots of trap catch versus damage is so scattered as to make such adjustments insignificant.

Table 15. Confidence intervals ( $\alpha=0.05$ ) for a binomial parameter  $p$  when sample size  $n=200$ . These values are based on the equation:  $p \pm z_{\alpha/2}\sqrt{p(1-p)/n}$ . This equation was taken out of Bhattacharyya and Johnson (1977). Note: if the table were continued to  $p$  estimate values of 1.0 it would be symmetrical and confidence intervals would decrease.

p estimate	95% C.I.
0.01	$\pm 0.014$
0.05	$\pm 0.030$
0.10	$\pm 0.042$
0.20	$\pm 0.055$
0.30	$\pm 0.064$
0.40	$\pm 0.068$
0.50	$\pm 0.069$

#### Assumptions in the Determination of Moth Population Levels

Moth concentrations at each planting was modeled as a function of corn development stage based upon oviposition preference studies conducted by Johnson et al. (1975). In this study they looked at relative concentrations of eggs on plants caged with 25 pairs of moths and on crops in the field. From these observations, they were able to come up with a matrix of relative ovipositional preferences for four crops and up to 16 stages per crop. It is these relative ovipositional preference values that are used in the simulation model as indications of male moth concentrations. It would have been preferable to use actual data of male moth concentrations versus crop stage, but such data were not available. Whether or not a connection can be made between ovipositional preference and male moth

concentrations can be debated. Males are more likely to be responding to virgin female moths, whereas the gravid females are the ones that are laying the eggs. I have no access to information showing whether or not virgin and gravid females show the same preferences for habitats. Males also could have different habitat preferences from females, gravid or not. Despite these potential problems, I would argue that if one is using pheromone traps to predict damage levels, the assumption that male moth concentrations are correlated with oviposition levels is built a-priori into your study. When pheromone traps are used as damage indicators, trap catch is assumed to indicate oviposition levels, which is assumed to indicate subsequent population levels of juveniles, which is assumed to indicate subsequent levels of damage. That pheromone traps have been used with some success in the past to make damage predictions provides evidence that these assumptions are reasonably correct.

#### A Re-examination of the Pheromone Emission Response Model

The pheromone emission response model (PERM) used in this study was a compromise between computational efficient and realism. Initially, a Monte Carlo random walk model was developed for the production of a pheromone emission response surface. For this model for each location around the pheromone trap the model would calculate the likeliness of capture for any moth by starting 100 moths at that location and seeing what proportion of moths would eventually cross the path of the pheromone plume. Moths crossing the plume were assumed to be captured by the trap. A random number generator and flat distributions were used to describe distances moved per flight segment and directions taken between flight segments. Angle and distance distributions were determined by using values that seemed reasonable based upon observations of moths in flight in the field. If a moth had not crossed the pheromone plume by search time "T" then it was called a non-capture.

Figure 25 shows an example of a PERM created in such a manner. For this figure, the trap occurs at position (5.5, 5.5) in the center of the graph. Lines represent isolines of probability. This figure can be compared with the PERM created by the model that was eventually used (Figures 11, 12, 20, 21, AND 22). Two interesting differences become apparent upon comparison of these figures.



First, in the random walk model the probability of capture does not drop off to zero for locations outside of the plume active surface and directly upwind and downwind of the trap (though plume active space is not shown in figure 26 it certainly can be assumed that it does not occur upwind of the trap). If moths make short movements and turn large angles this result makes more sense intuitively. In this case, moths just downwind of the far end of the plume active space should probably still have a reasonable chance of finding that plume in the process of randomly moving about in the field. A second difference is that moths located just downwind of the trap have a slightly less chance of being captured than moths positioned further downwind of the trap (position (5.5,5.0) versus (5.5,2.75)). Though this is not immediately intuitive, it probably results from the fact that moths that move away from the plume and upwind can still swing back towards the plume and cross it when positioned farther downwind. Moths positioned just downwind of the plume following that path will miss the plume altogether.

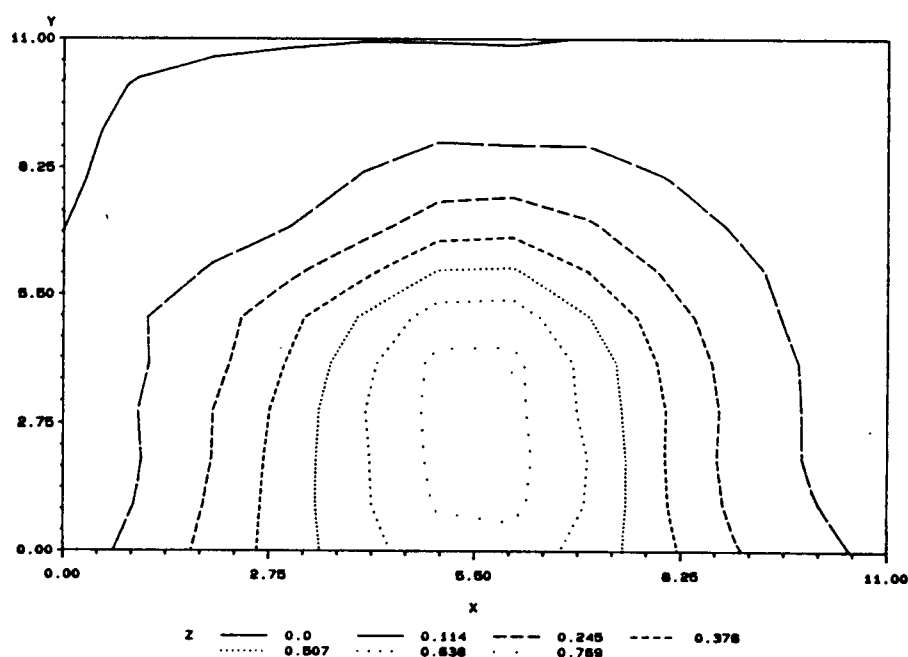


Figure 26. A pheromone emission response surface created as the result of a random walk process. The pheromone trap is located at position (5.5,5.5). Wind is blowing down the Y axis. Lines are isolines of probability of catch.

The simplified PERM was chosen because the random walk PERM was computationally much more time consuming. For the simplified PERM a single equation could be used to produce a likeliness of capture for each location around the trap. As has already been noted, the entire simulation model already was computationally expensive. It was only possible to do two runs of the model within any 24 hour period using the computer facilities available. For each year 30 sites were modeled and for each site pheromone emission response surfaces had to be created for roughly 10 to 20 days. This means that somewhere between 300 and 600 response surfaces would have to be created for each run of the model. The addition of that many runs of the random walk PERM would have seriously impaired any attempts to optimize parameters or check the model for sensitivity. Additionally, as the range of potential moth turning angles is decreased and the length of flight paths between turns increased, the random walk PERM starts to look more and more like the simplified PERM. Moths observed flying in the field in daylight during trap checks generally seemed to move in a single direction. No observations were made of moth movements at dusk when moth activity levels are highest. Nevertheless, because of these observations and for computational efficiency the simplified PERM was chosen. It was hoped that even if the simplified PERM was not optimally realistic, that the use of it would still provide enough information to improve trap catch interpretations.

#### A Re-examination of Assumptions Made by the Simplified Pheromone Emission Response Model on Male Behavior Outside of the Pheromone Plume

The simplified PERM used in this study allows for two basic assumptions to be made about the flight orientation of male moths when not in contact with a pheromone plume: 1) that flight orientation is completely random and each of the 360° directions is equally likely to be taken, and 2) that flight orientation will be cross-wind as a means of most efficiently coming into contact with a plume. However, Sabelis and Schippers (1984) in a modeling exercise were able to provide compelling arguments that under conditions of moderate to high wind direction variability, male moths increase their odds of detecting a plume by flying either upwind or downwind. In order to be energy efficient they would most probably fly

downwind. Sabelis and Schippers do not provide any field data to substantiate the claims of their model, but it does point out that normal assumptions of cross-wind search patterns may not be correct. More field research is needed on male moth behavior when not in contact with a plume. A question can be raised as to whether or not they even engage in plume searching behavior. It should be noted, however, that among all of the runs of the simulation model, the one that produced the strongest subsequent correlation between trap catch and damage was a run that used a cross-wind plume searching pattern.

### Management Recommendations

Funding for much of this research came from the Oregon Processed Vegetable Commission and therefore the intent of the study was to provide recommendations to processed corn growers as to the best method for monitoring earworm levels. In this section I will present what I believe would be an optimal use of the information gained from this study. The material presented in this section will include some ideas that are still not conclusively proven, although evidence is available for their inclusion. For example, it was observed earlier that damage levels seemed to be especially severe when trap catch peaks were well synchronized with silking peaks. This hypothesis was based on observations made over only four years and therefore needs to be verified over more years before it can gain strong scientific credibility. Nevertheless I will incorporate this conclusion into the monitoring recommendations.

Because of the high variability to be found for the trap catch versus damage levels from individual sites, it would be preferable that any monitoring effort be conducted by one or a few central locations each with access to data from several traps. This function could be supplied by private consultants or by cannery field personnel. Since the corn earworm is usually not a problem for growers and they would prefer to expend a minimum effort in monitoring activities, it would be better to have a trapping program come in at least two phases. These would include a low level phase and a high level phase. The low level phase would require a minimum of effort, would not provide enough site-specific information for high damage years,

but would inform growers when such years occurred. At that point a more intensive trapping operation could be started.

An example low level trapping operation would be to place 5-6 traps regionally, starting in mid-July and check those traps once a week. Traps should all be placed in different aged plantings excluding the earliest plantings. Though no data indicates within-valley regional differences in trap catch or damage levels, it would be best if traps were not confined to one small area within the valley. Traps should be separated by at least 10 kilometers. As much as possible, traps should be placed away from wind blocking features such as tree rows, wooded areas, or abrupt hillsides. In addition to moth catch levels, corn development levels should be monitored as well. On a weekly basis aggregate corn phenology should be noted. Specifically, it should be noted whether or not a noticeable minority ( $> 5\%$ ) of corn plants are silking for as many corn plantings as possible (at least 20). The age distribution of plantings checked for silking should approximate that of plantings throughout the valley (i.e. if 20% of the plantings throughout the valley were planted after June 1st then 20% of the sampled plantings should have also been planted after June 1st).

Two indications of high damage years will be used: 1) high trap catch levels, and 2) high synchrony between peaks in trap catch levels versus the number of silking plantings. If at any point the average weekly trap catch exceeds 100 moths per trap then chances are good that some locations within the valley will sustain economic damage levels that year. Conservative operators might consider implementing phase II monitoring methods at that point. This 100 moth level is based on the fact that two of the three years where we observed low damage levels (1989 and 1991) had average weekly trap catches that peaked at less than 70 while the one observed moderate damage year had average weekly trap catches peak at 245. The value of "100" falls between these two levels and is conservative as an indication of potential for moderate to high damage. If in addition to high moth catch levels, it is noted that trends in moth catch and in the number of silking plantings are in synchrony, then the potential for high damage at some locations within the valley is strong and phase II monitoring levels are recommended. As an example of years with low synchrony look at Figures 23a, 23c, and 23d. A year with high synchrony is shown in Figure 23b. The addition of this second criterion comes from the fact that one low damage year had peak weekly catch levels that exceeded 100 (1990) and therefore would have passed the moth catch criterion for

high damage years, however this year had low synchrony between trap catch and silking trends and therefore by the second criterion would correctly not be identified as a year with potential for high damage. It should be noted that none of the four years passed both criteria for high damage.

For phase II monitoring, as many traps as possible should be placed in all corn plantings that have not already started tasseling. Since we have already used trends in silking as an indication of the need to enter phase II monitoring, these pre-tasseling plantings will be late plantings of corn. Monitor these plantings twice a week and note 1) the date when silking is first observed in the planting ( $> 5\%$  corn plants silking) and 2) the cumulative moth catch between the first day when tassels can be seen emerging from the leaf whorls (on  $> 5\%$  of corn plants) and the date of first silk. Enter this information into the CEWSIM computer program (Coop et al., 1993). Note that if many large plantings of corn surround your planting then CEWSIM will probably exaggerate the damage potential. "Many large plantings" can be defined as situations when there are more than 140 hectares of corn within 2 kilometers of the pheromone trap. If there is little corn around the trap then the CEWSIM program may underestimate the damage potential. "Little corn" can be defined as situations when there are less than 60 hectares of corn within 2 kilometers of the trap. These definitions of "little" and "large" amounts of corn are based on the upper and lower 1/3 of corn area values observed in our sample sites over the course of this study.

CEWSIM provides information on infestation rates, the likely distribution of damage, and the benefit cost ratio for a proposed chemical application. One or two chemical applications spaced 7-14 days apart and occurring during silking are maximum for earworm control in processed corn in the Willamette Valley. Though chemical control methods are specifically dealt with in CEWSIM and are the current standard approach to earworm control, there is nothing to the damage prediction model that intrinsically requires a chemical management approach. If effective alternative approaches become available (ex. a biorational pesticide or the inundative release of a predator or parasite), then these methods will still benefit from the information gained from this predictive model.

## Summary

The most effective way to have come up with a method for predicting high damage years would have been to have observed several high damage years and several low damage years and seen what differences occurred between the two types. Over the course of six years of monitoring corn earworm in sweet corn with pheromone traps we never were able to observe conditions for a high damage year. For the two years in which I included spatial information to the analysis, damage levels were extraordinarily low. With these limitations in the data sets the best that can be done is see what conditions occurred at locations with relatively high damage and extrapolate those conditions to high damage years. Until a high damage year occurs, pheromone traps are placed and monitored as recommended, and model behavior is more completely analyzed, we will never be very sure how well the model performs under high density circumstances. Despite the uncertainties as to the accuracy of specific predictions made by the model, some observations have been made that would be useful for the proper interpretation of pheromone traps. It has been shown that large acreages of corn surrounding the trap will raise moth catch levels within the trap so that in order to get an accurate prediction of damage within the trapped planting, the damage prediction will have to be lowered. Surprisingly, no evidence could be found to show that particular age classes of corn surrounding the trap could have a stronger effect than others. In fact, for both the regression analysis and the simulation model, model performance was enhanced when corn age was not taken into account in the analysis. Secondly, it was shown that the presence of wind blocking features close to the trap on the north side tended to lower moth catch so that damage estimates had to be raised under such conditions. Finally, circumstantial evidence indicated that a high synchrony between valley-wide moth catch levels and valley-wide proportions of silking plantings could be used as an indicator of high damage years.

Damage levels observed over the two years of this project were never high enough to allow adequate testing of the model. Therefore it was only able to produce a slight and not significant improvement in the correlation between cumulative trap catch and subsequent damage. Despite the extraordinarily low damage levels, evidence was available indicating that the model was in fact functioning properly. It is probable that a better performance would be obtained from the model in a high damage year.

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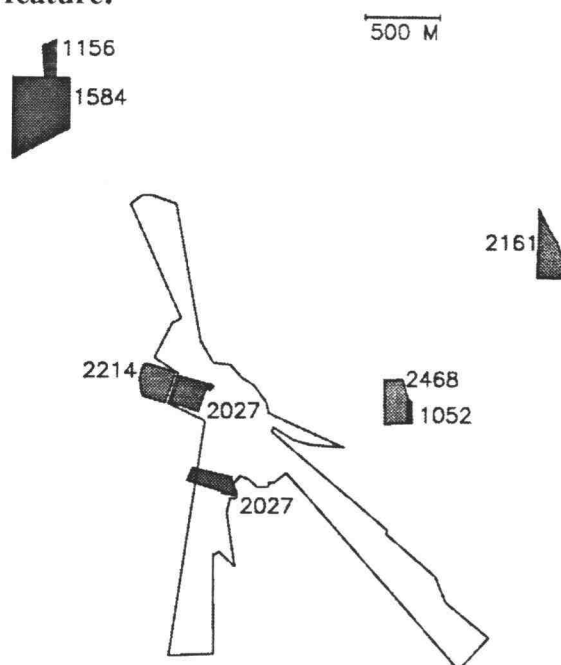
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## Appendices

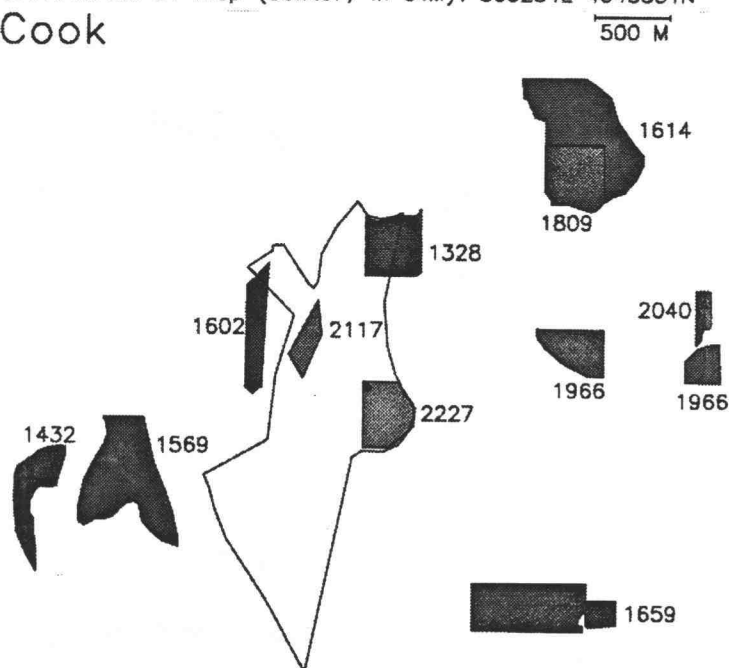
**Appendix A: Maps of all trapped plantings and the surrounding 2.5 km radius. Numbers next to plantings indicate their degree day development as of August 5. Traps are marked as small diamonds at the center of every map. The uncolored, irregular figure around each trap shows all locations with an unobstructed line-of-site to the trap. All other locations are blocked at some point by a wind blocking feature.**

**Bose**  
1990 MAPS:



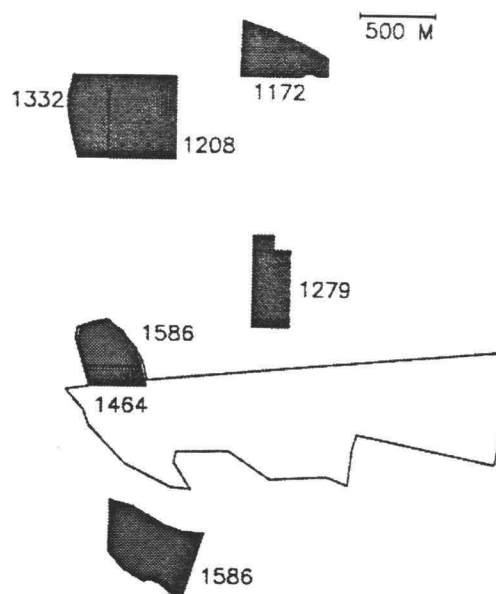
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**Cook**



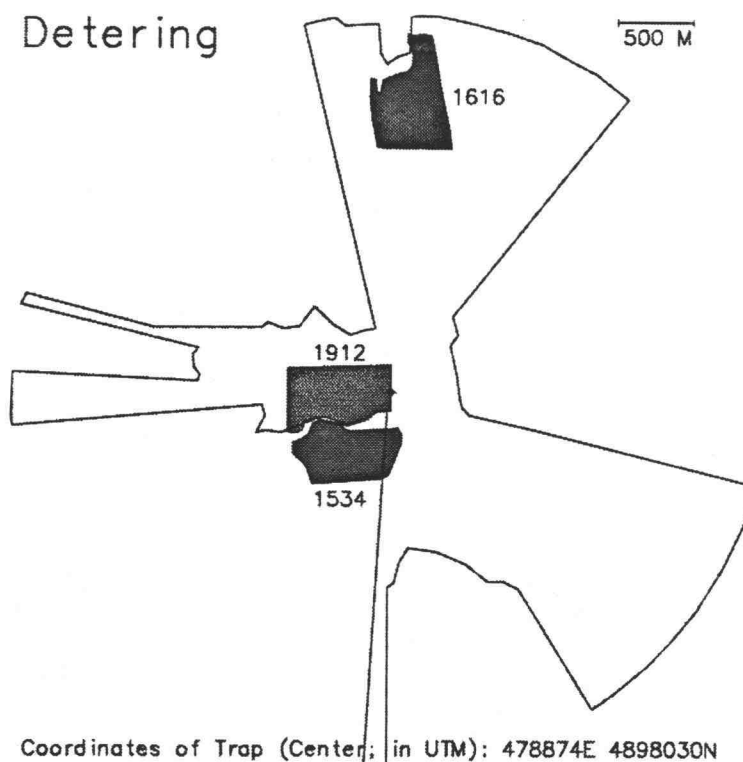
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## Calef



Coordinates of Trap (Center; in UTM): 486479E 4964575N

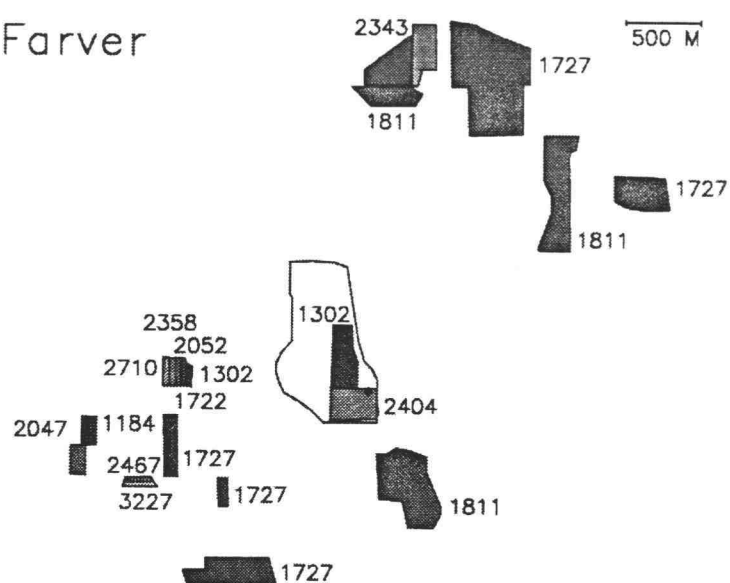
## Detering



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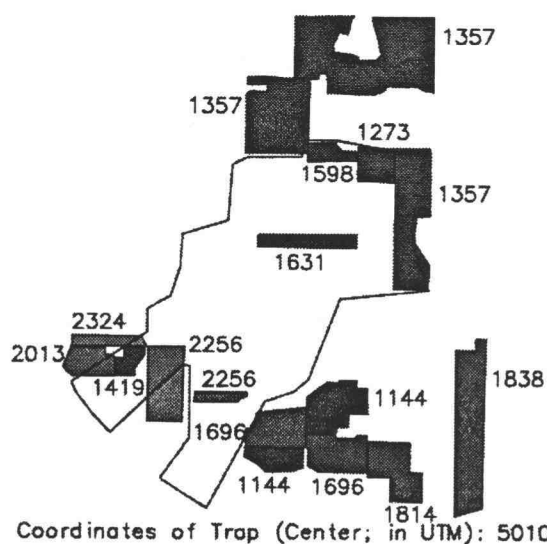


Farver



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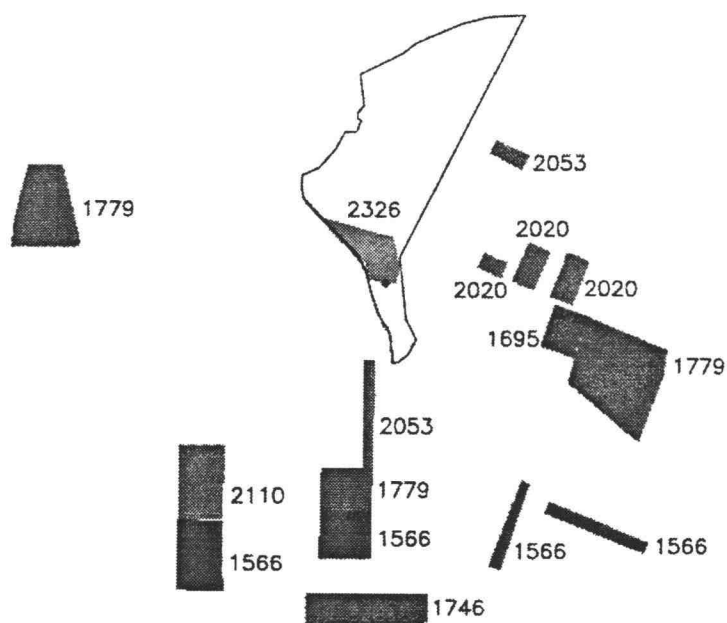
Ferguson



Coordinates of Trap (Center; in UTM): 501024E 4951407N

## Gilmour

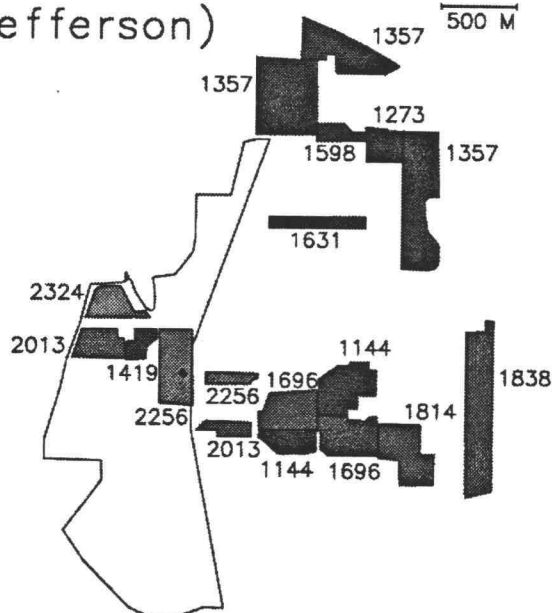
500 M



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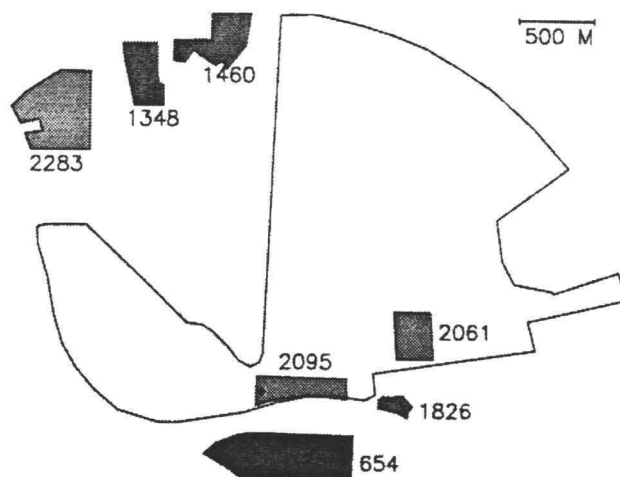
## Gray (Jefferson)


500 M



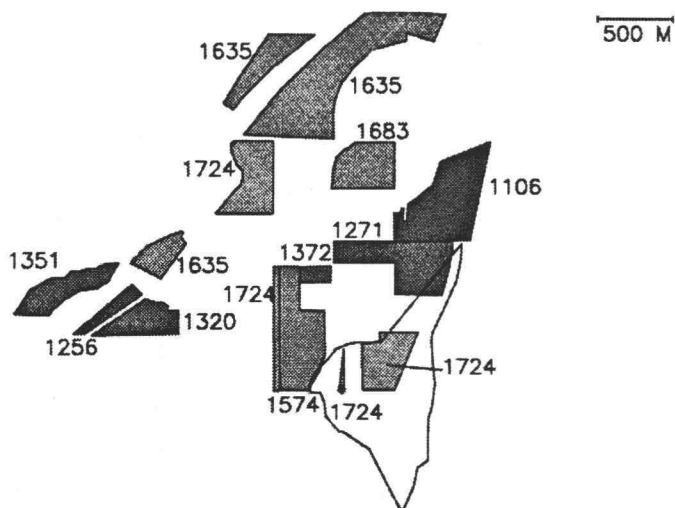
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Gray (Millersburg)  2283  
1834 (inner)

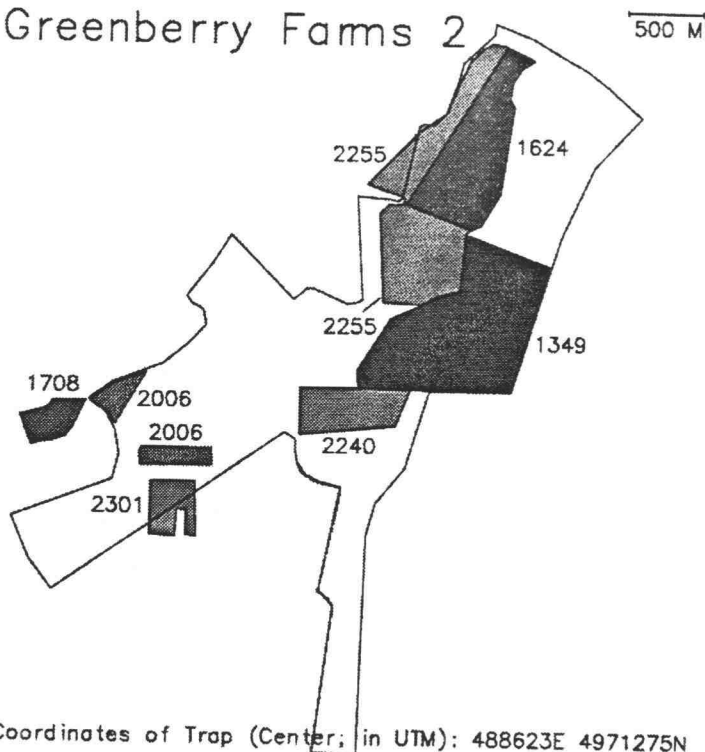
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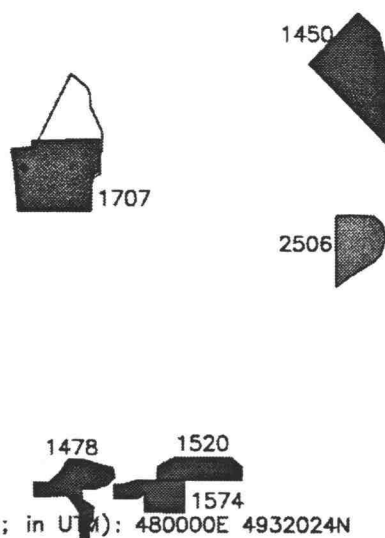
Greenberry Farm 1

Coordinates of Trap (Center; in UTM): 488228E 4970263N

## Greenberry Farms 2

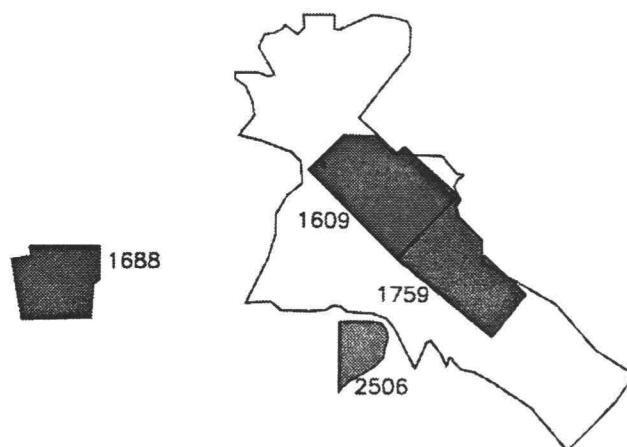


## Hamlin (Corvallis)



## Hamlin (Peoria Rd.)

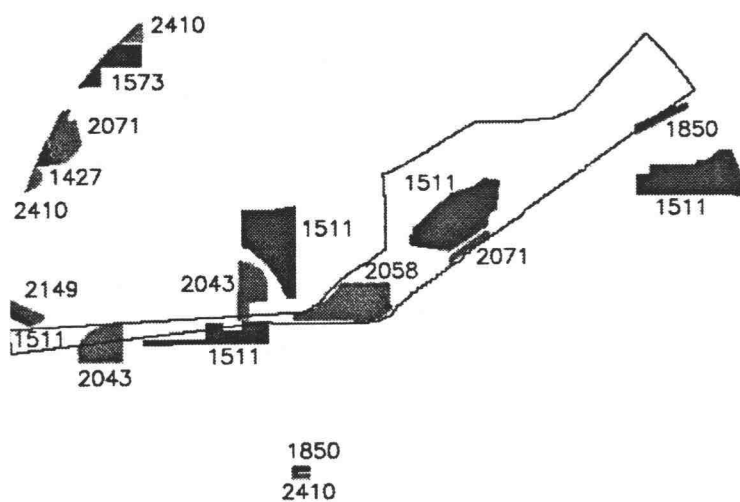
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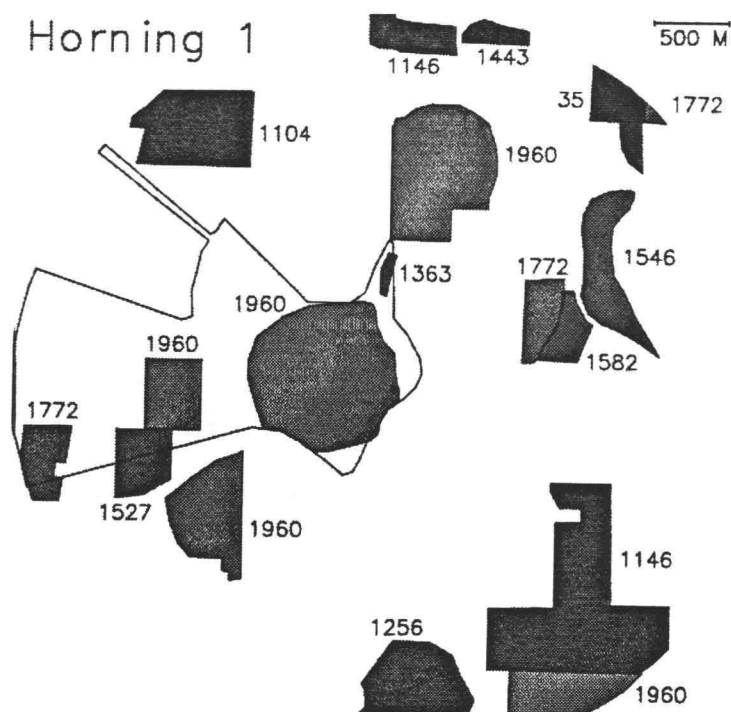
## Henderson

500 M



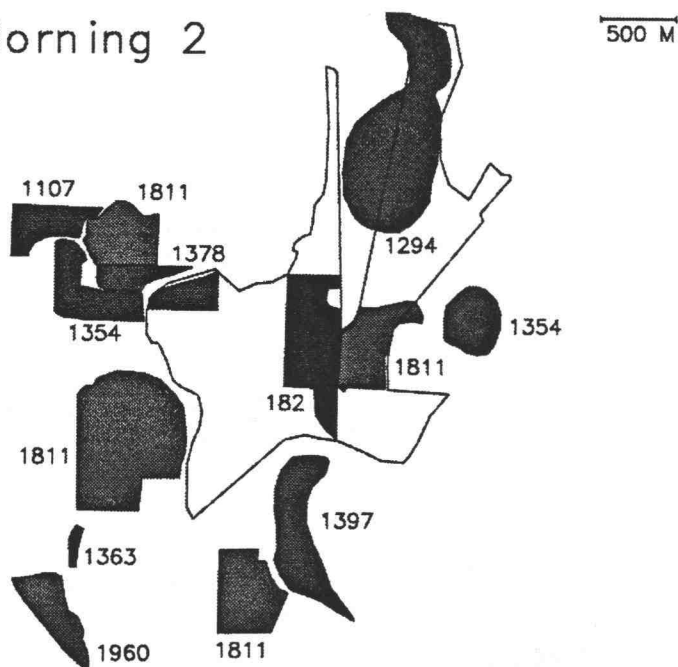
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# Horning 1



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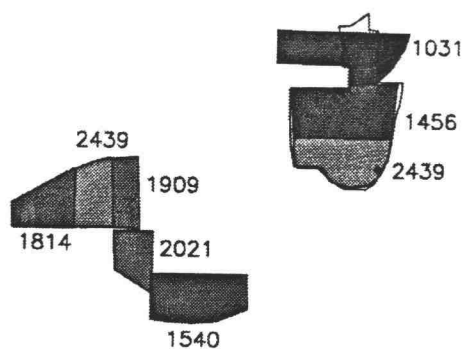
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Iverson

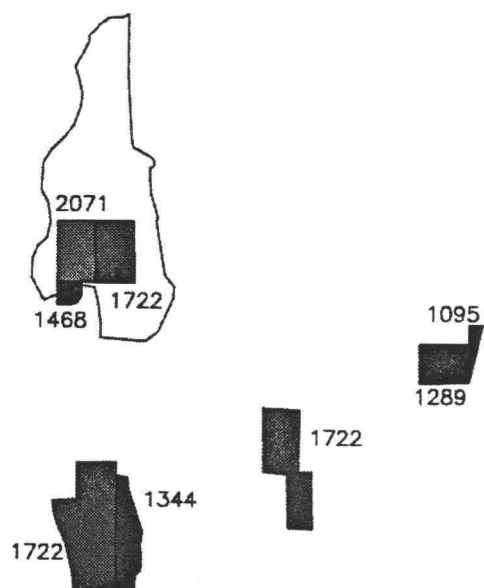
500 M



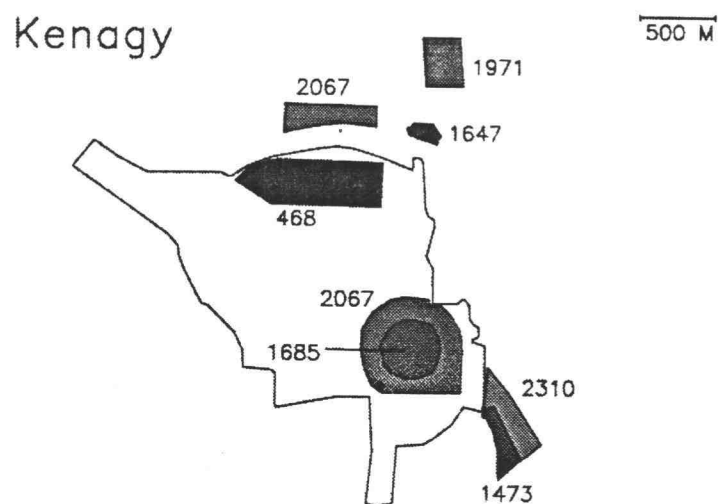
Coordinates of Trap (Center; in UTM): 493928E 4973671N

Jones

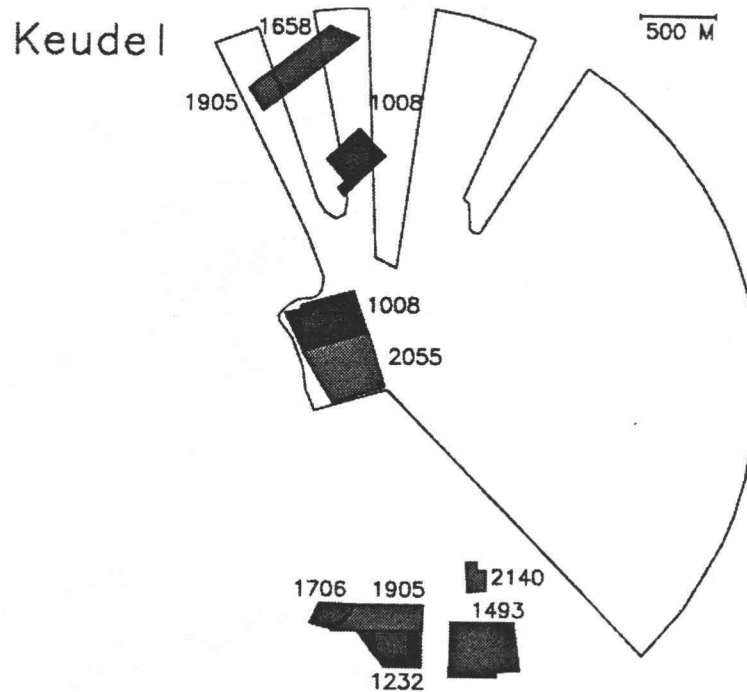
500 M



Coordinates of Trap (Center; in UTM): 480012E 4922695N



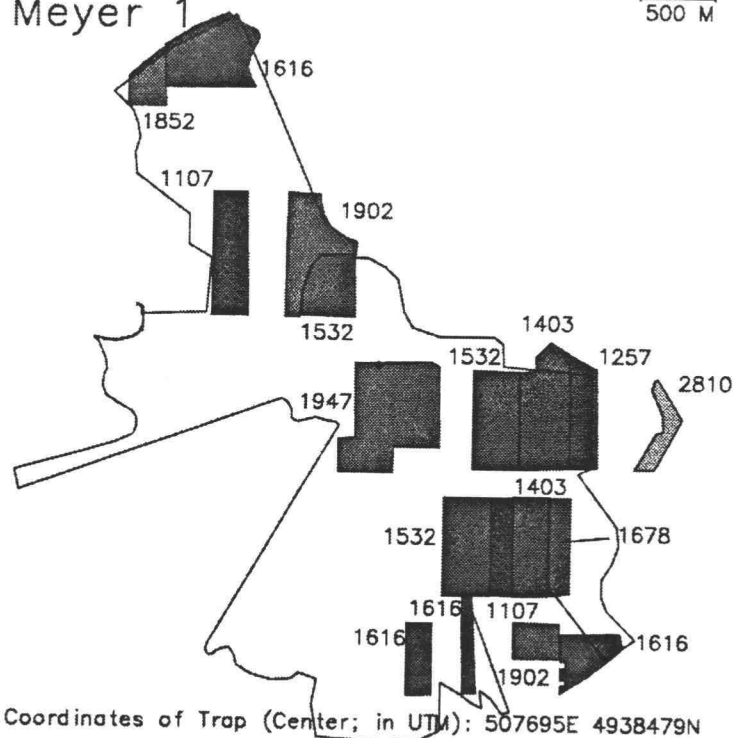
Coordinates of Trap (Center; in UTM): 492671E 4945096N



Coordinates of Trap (Center; in UTM): 504072E 4959048N

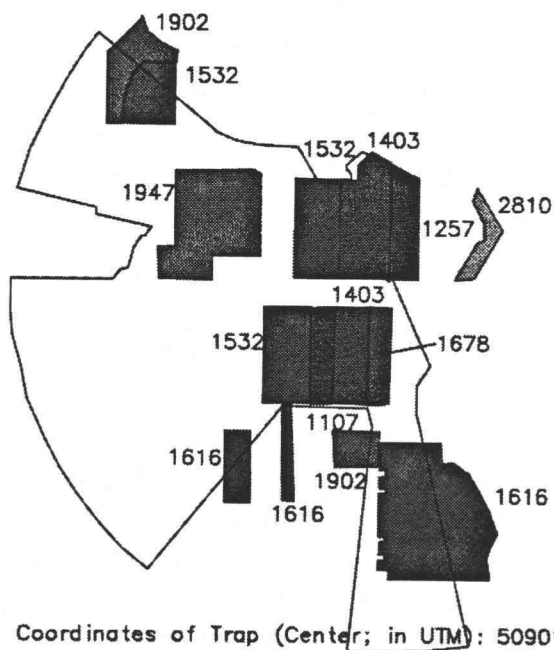
## Meyer 1

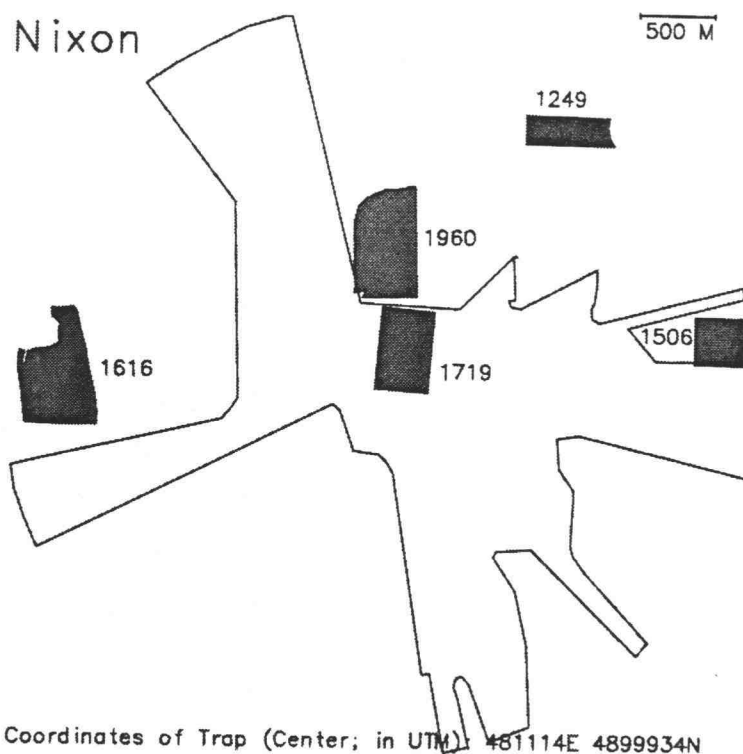
500 M



## Meyer 2

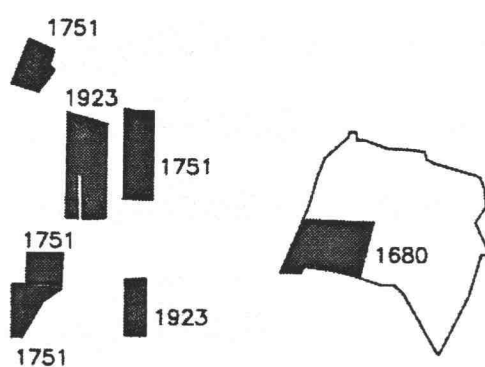
500 M





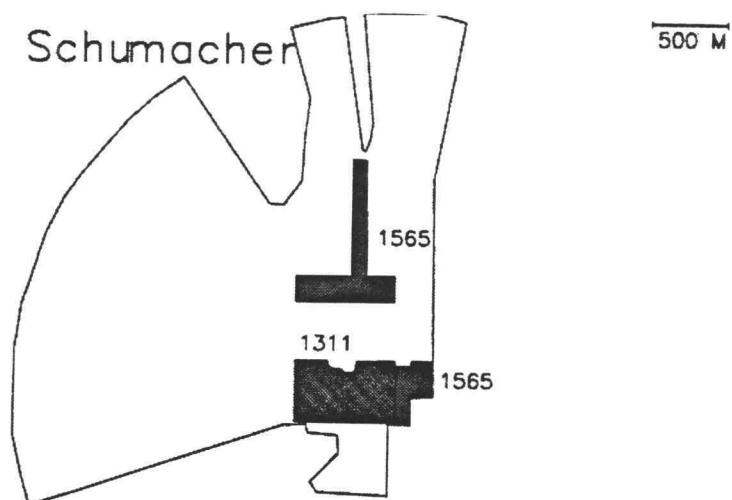
Schlegel

500 M



Coordinates of Trap (Center; in UTM): 485563E 4938228N





Coordinates of Trap (Center; in UTM): 509263E 4968844N

## 1991 MAPS:

## ARS Farms

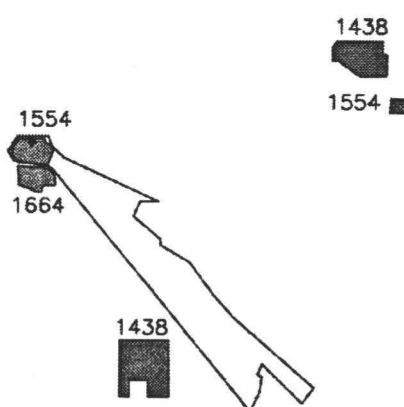
500 M



Coordinates of Trap (Center; in UTM): 517664E 4967946N

## Bose

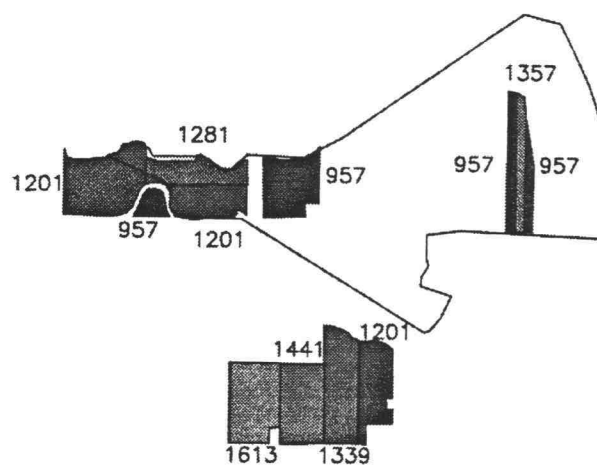
500 M



Coordinates of Trap (Center; in UTM): 503586E 4943263N

Cook

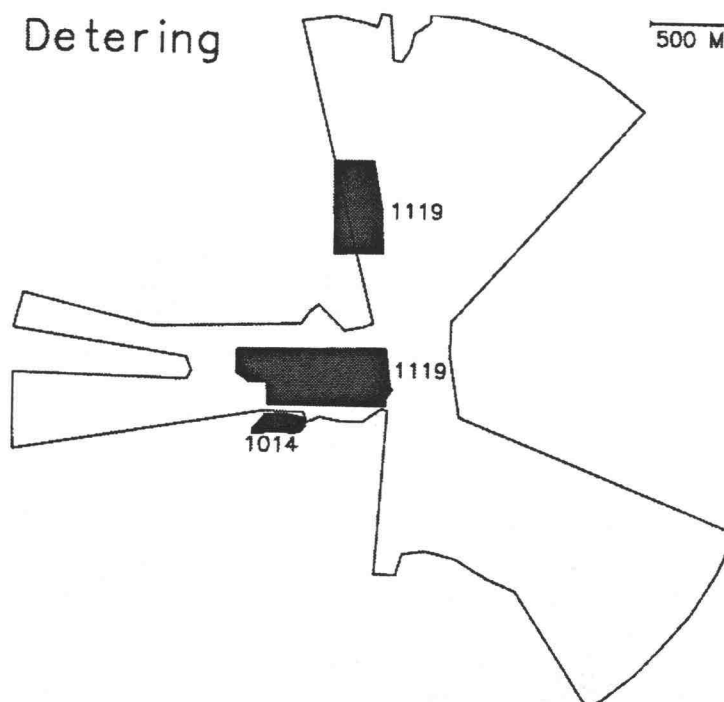
500 M



Coordinates of Trap (Center; in UTM): 490569E 4952826N

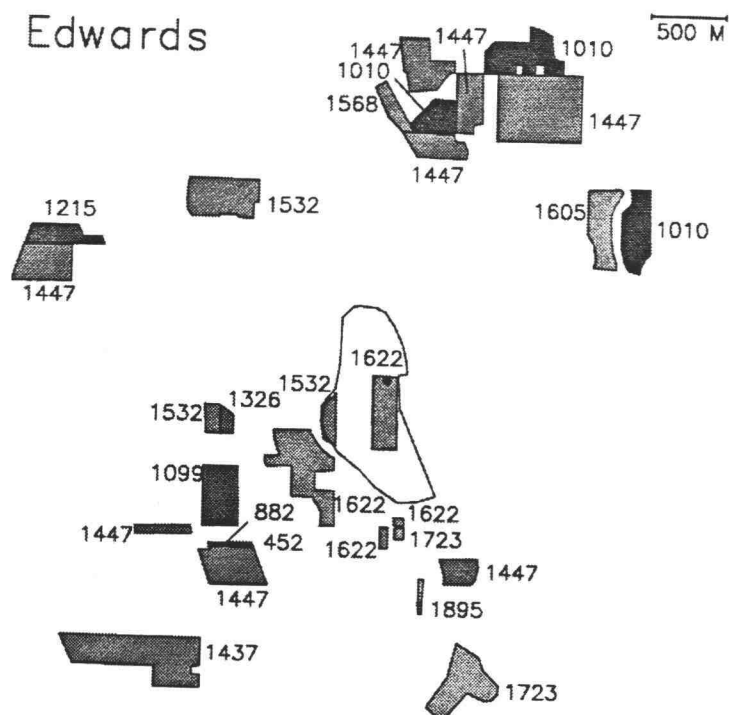
Detering

500 M



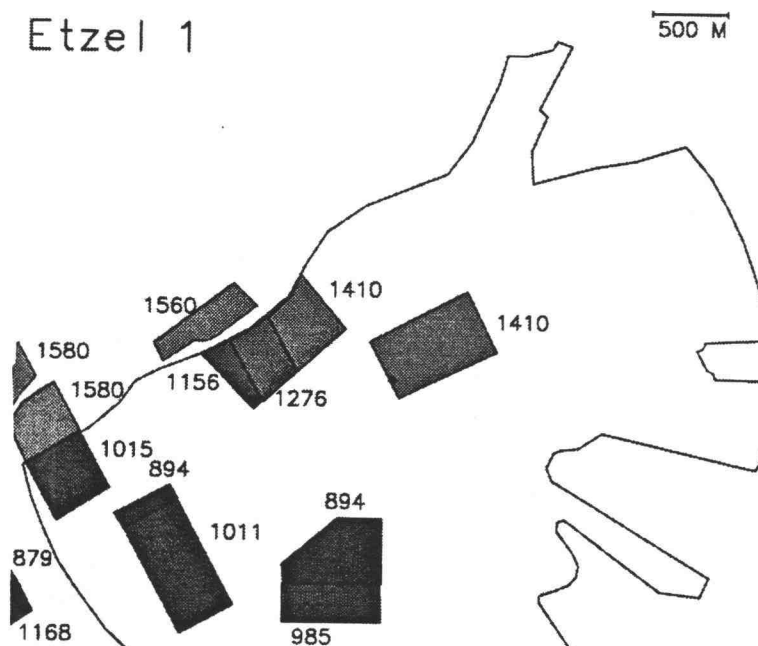
Coordinates of Trap (Center; in UTM): 478874E 4898030N

## Edwards



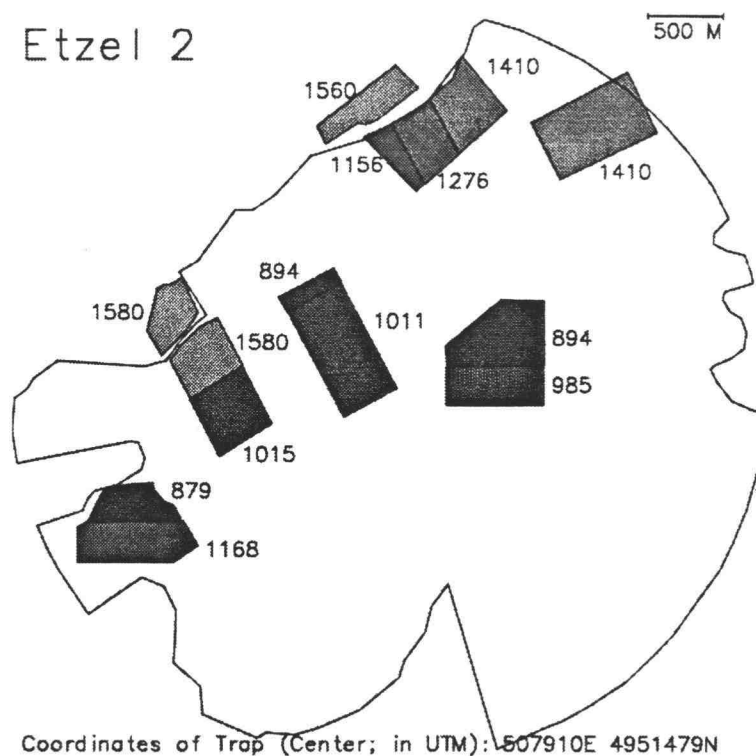
Coordinates of Trap (Center; in UTM): 488671E 4890623N

## Etzel 1

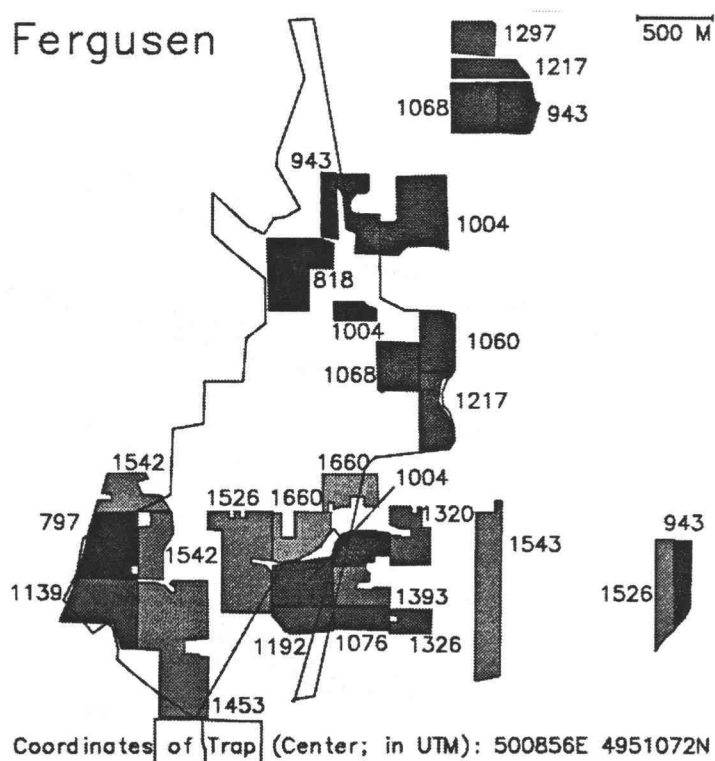


Coordinates of Trap (Center; in UTM): 508976E 4952982N

## Etzel 2

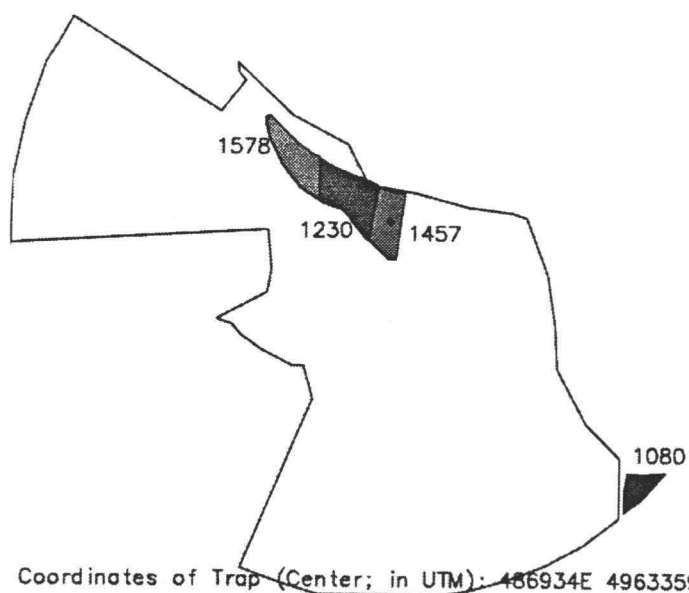


## Fergusen



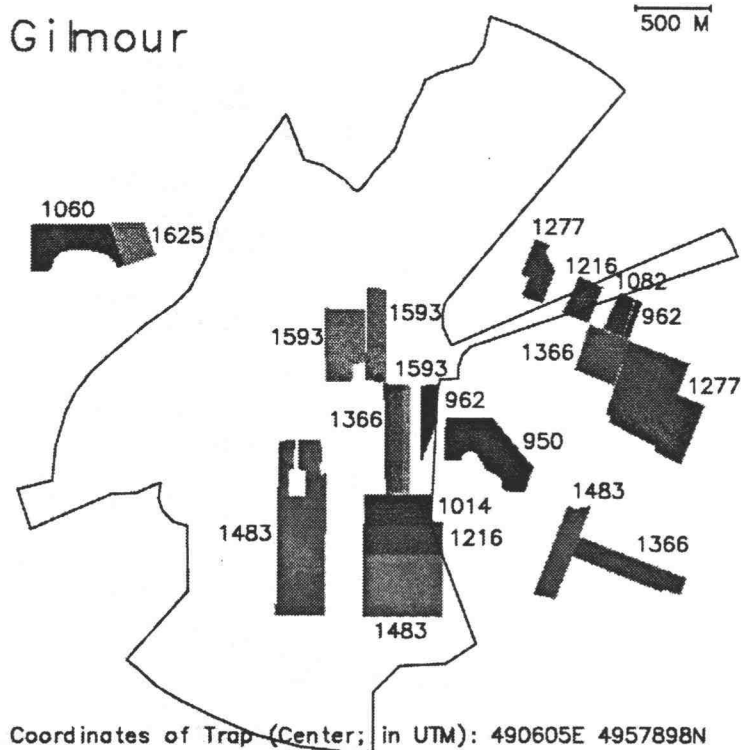
## Giesbrecht

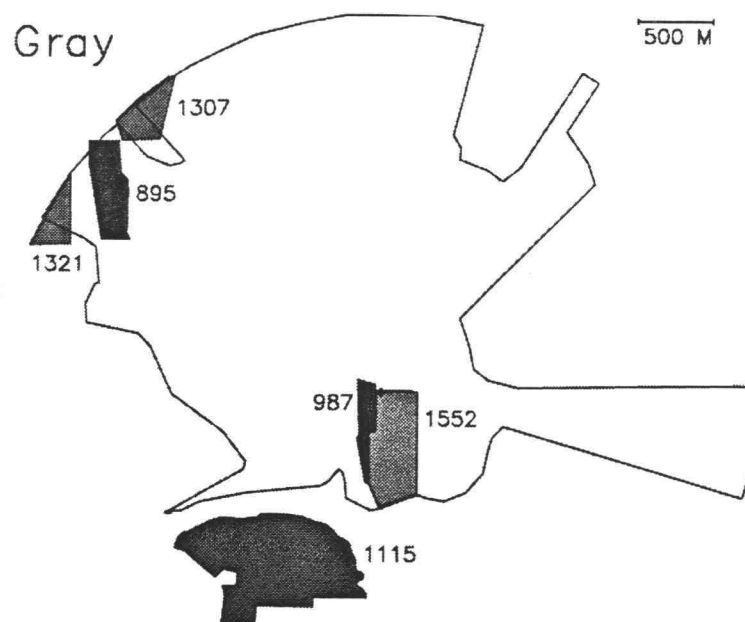
500 M



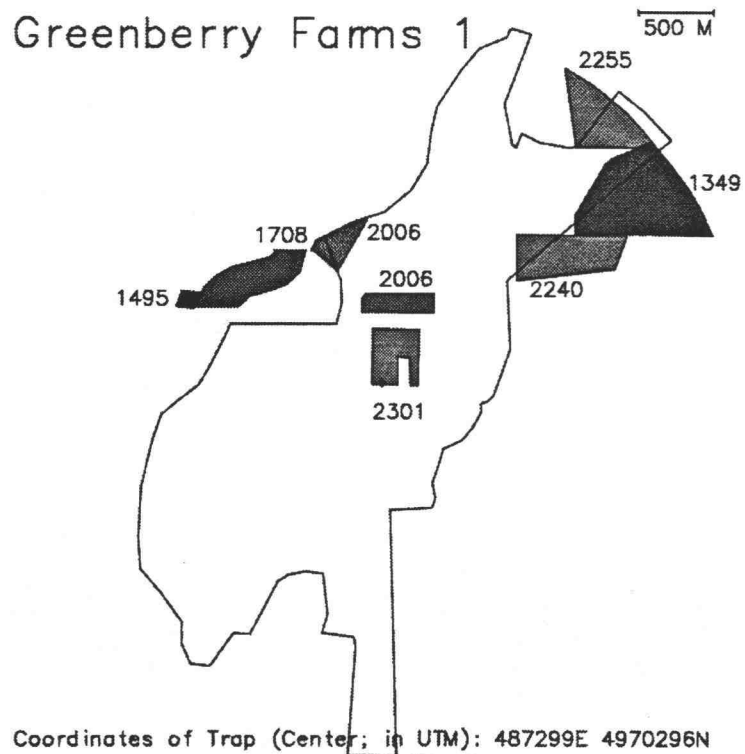
## Gilmour

500 M

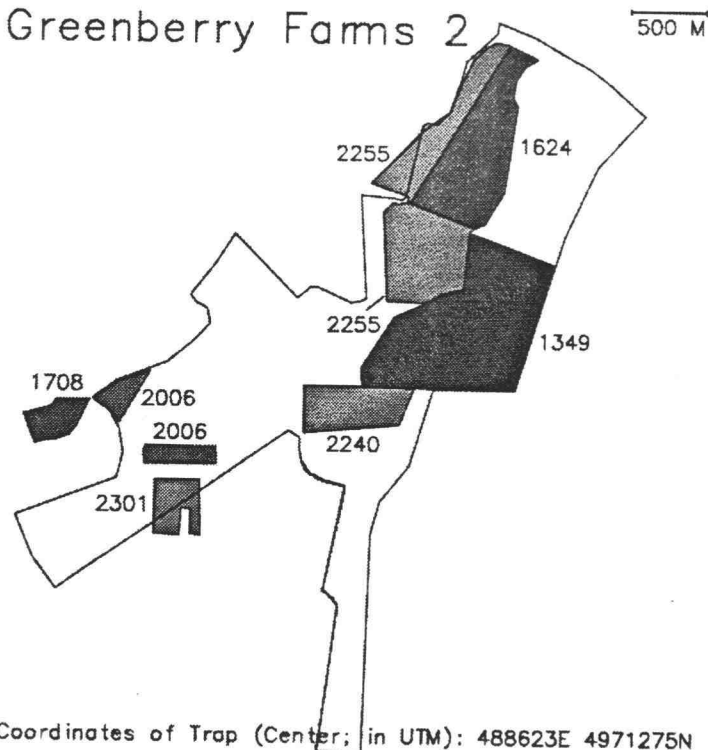




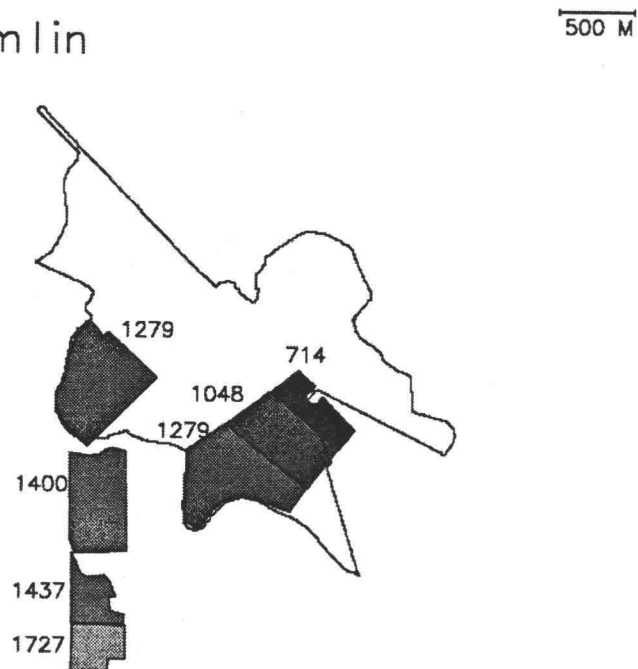
Coordinates of Trap (Center; in UTM): 490605E 4957898N



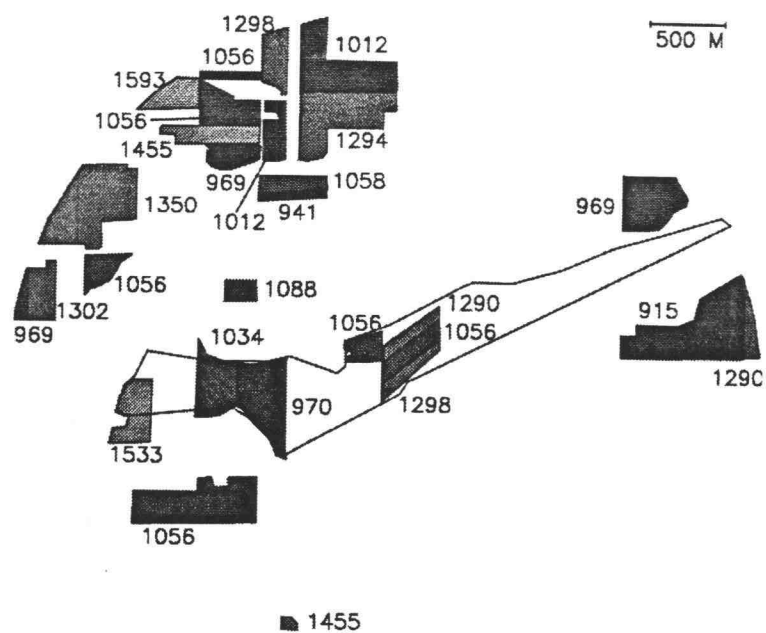
# Greenberry Farms 2



# Hamlin



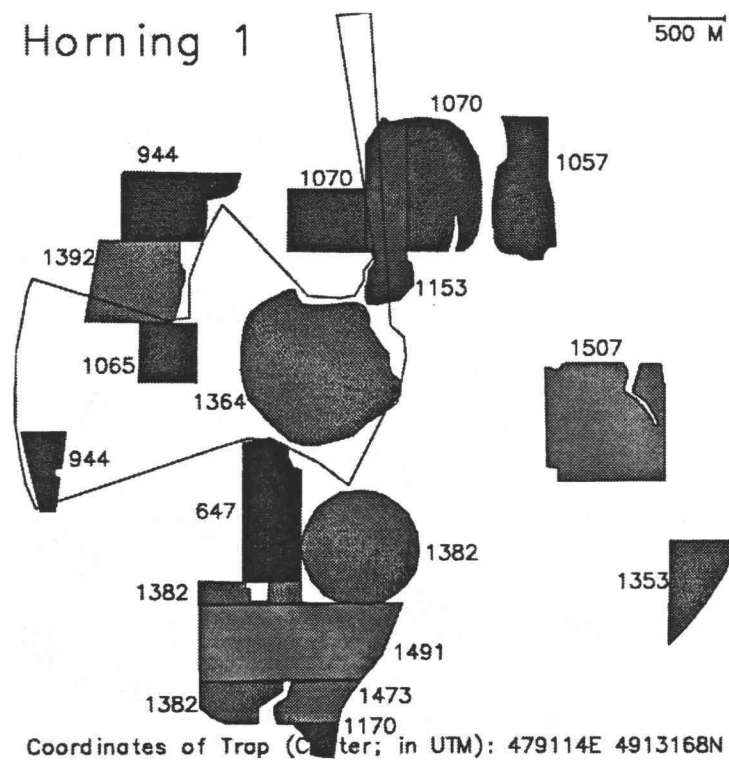




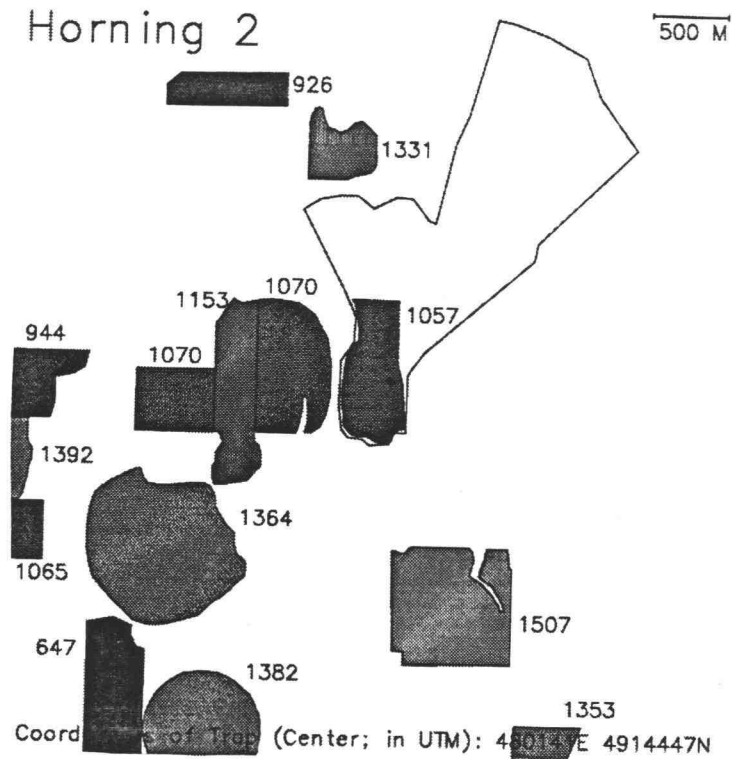
## Henderson

Coordinates of Trap (Center; in UTM): 513994E 4956479N

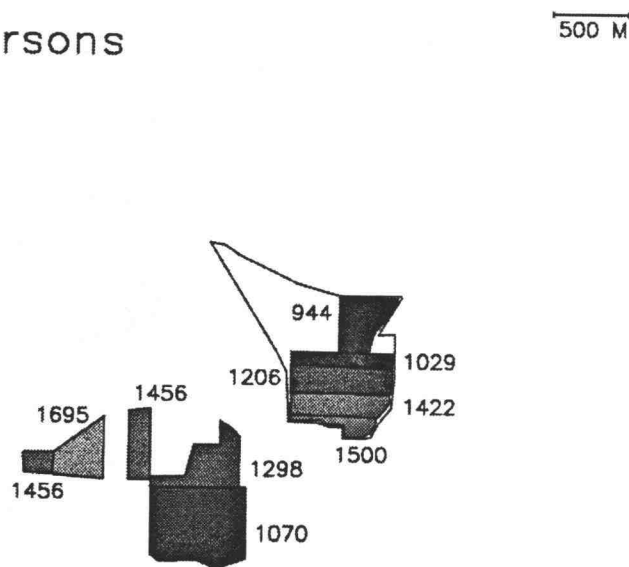
## Horning 1

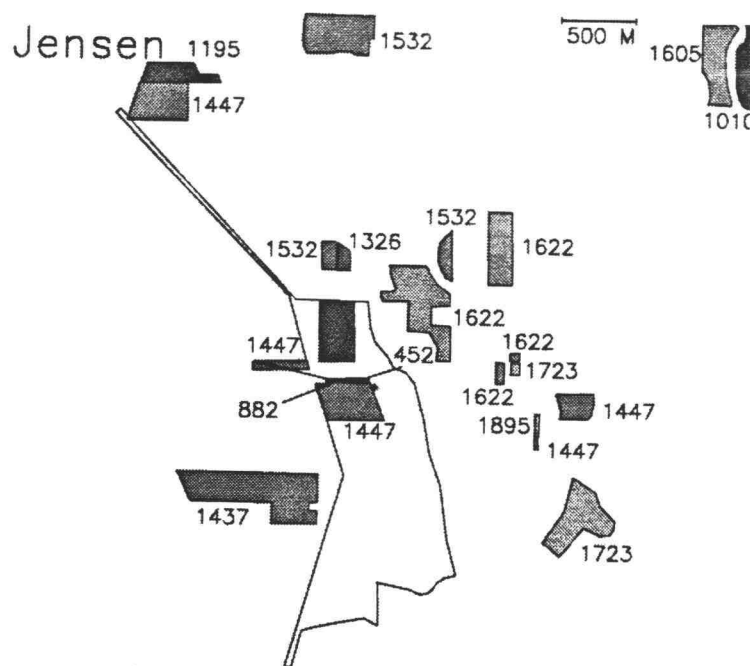


# Horning 2



# Iversons

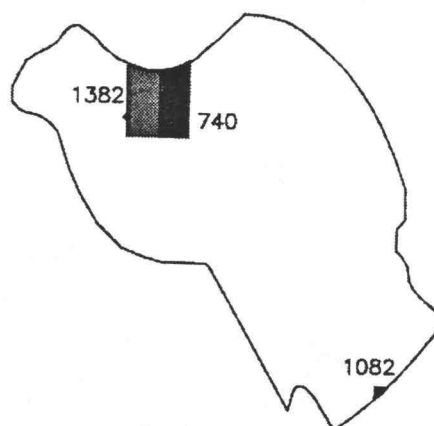




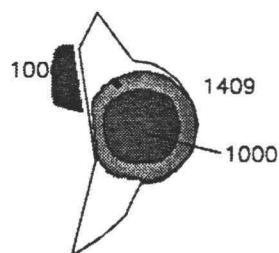
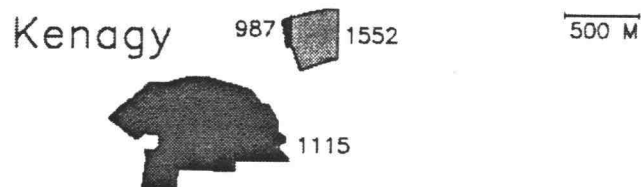
Coordinates of Trap (Center, in UTM): 487934E 4889503N

Jones

500 M

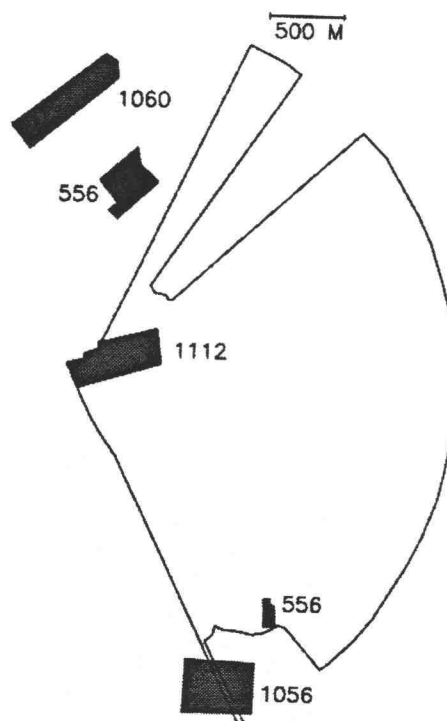


Coordinates of Trap (Center; in UTM): 480757E 4923849N



Coordinates of Trap (Center; in UTM): 493623E 4944623N

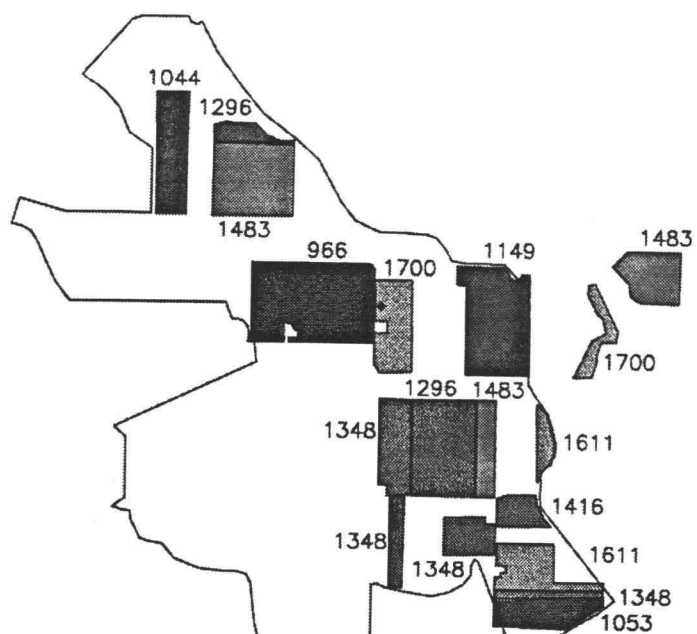
Keudel



Coordinates of Trap (Center; in UTM): 503575E 4959527N

Meyer

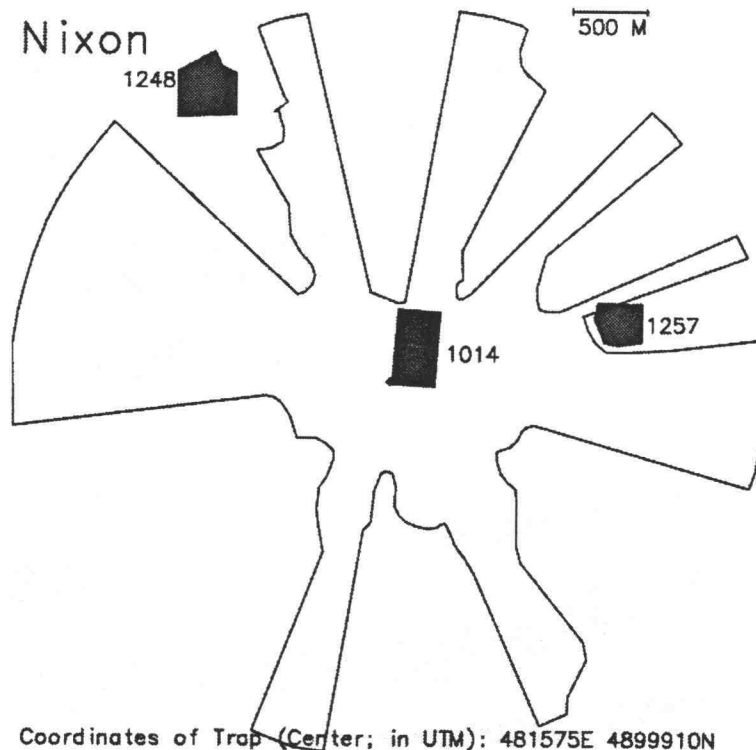
500 M



Coordinates of Trap (Center; in UTM): 508167E 4938214N

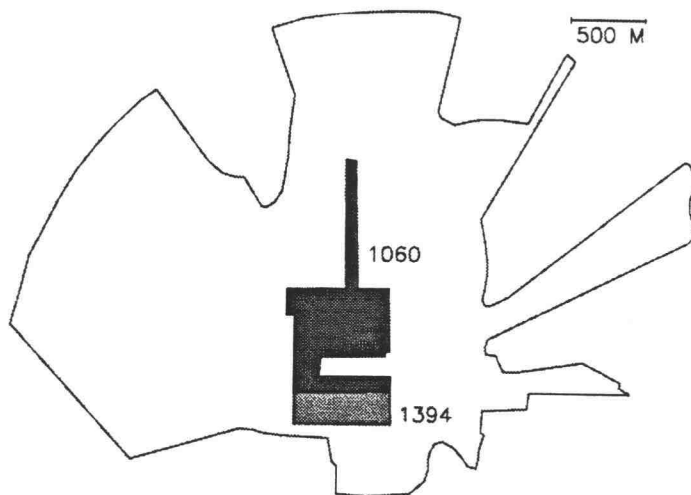
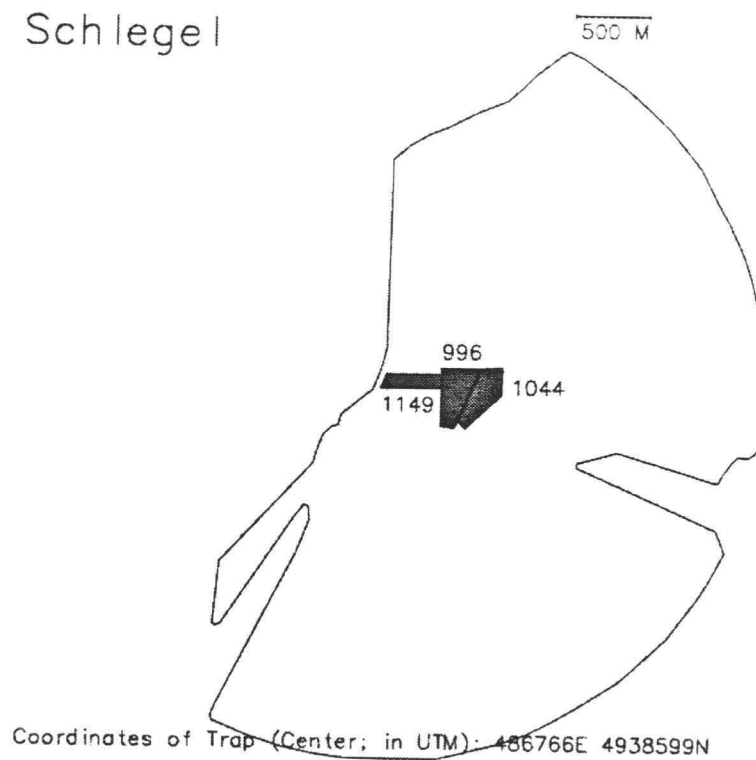
Nixon

500 M



Coordinates of Trap (Center; in UTM): 481575E 4899910N

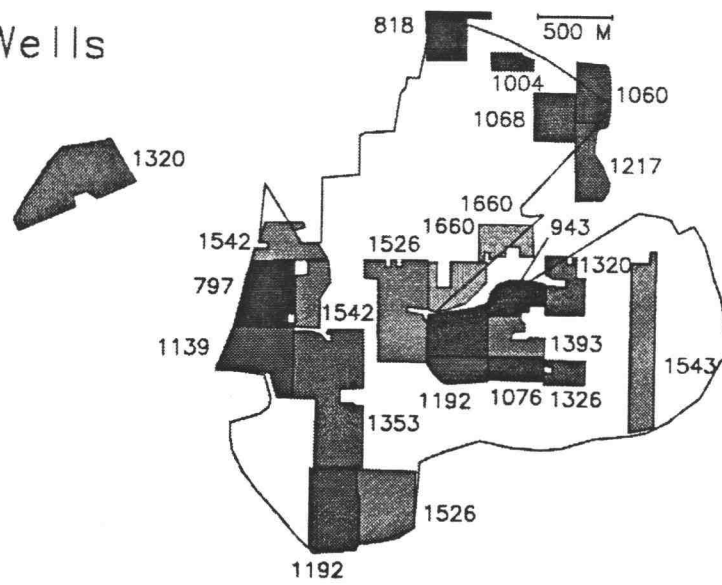
## Schlegel



## Schumacher

Coordinates of Trap (Center; in UTM) 509228E 4968826N

## Wells



Coordinates of Trap (Center; in UTM): 499647E 4949431N

## Appendix B: Unix Script Files Used in the Catch Modification Model.

**File 1: model.90a is the main script file which calls all other script files and programs. This particular example was used for 1990 data. Because of differences in parameters used, files accessed, and in formats of some weather station data files, a slightly different script file had to be written for 1991 data.**

```
### GENERAL CEW DYNAMIC PHEROMONE INTERPRETATION MODEL
### PROGRAMMED BY RAY DRAPEK.
```

```
# Determine the earliest date for which some field is tasselling.(Fst1stTas)
# Determine the last date which some field has not silked yet. (Last1stSil)
# Also create a couple of other files which will prove usefull later on....
```

```
#Create.InfoFiles
```

```
DDAug5=`tail +2 hys90|grep "^217"|cut -d" " -f5|sed 's/\.[0-9]*//`
```

```
MaxSite=`cat sortsites|sed -n 'Sp`
```

```
Fst1stTas=`expr $DDAug5 - $MaxSite + 1327`
```

```
MinSite=`cat sortsites|sed -n '1p`
```

```
Last1stSil=`expr $DDAug5 - $MinSite + 1753`
```

```
# Fst1stTas & Last1stSil are in terms of DD, NOW convert to julien days
```

```
Fst1stTas=`tail +2 hys90 | FindIt $Fst1stTas 5 1`
```

```
Last1stSil=`tail +2 hys90 | FindIt $Last1stSil 5 1`
```

```
# For Each Day From Fst1stTas to Last1stSil do ...
```

```
Day=$Fst1stTas
```

```
while [ $Day -le $Last1stSil ]
```

```
do
```

```
DDToday=`tail +2 hys90|grep "$Day"|cut -d" " -f5|sed 's/\.[0-9]*//`
```

```
DDDiff=`expr $DDAug5 - $DDToday`
```

```
# If there are no sites with:
```

```
# 1) a catch > 0 today,
```

```
# 2) at least one planting that is between 1st tassel and 1st silk,
```

```
# 3) there is damage information for this planting
```

```
# then
```

```
# don't bother with any of the rest of the calculations.
```

```
GoOn=No
```

```
for site in `cat sites90|cut -d' ' -f1`
```

```
do
```

```
Catch=`tail +2 trap90|grep $site|FindIt $Day 1 3`
```

```
if [ `echo "$Catch -gt 0"|compare` -eq 1 ]
```

```
then
```



```

        for planting in `cat DamPlantings|grep $site|awk
' {for(i=2;i<=NF;i++) print$i}'`
        do
            # determine the current corn stage of that planting
            DDPlanting=`expr $planting - $DDDiff`
            # if (stage is between 1T and 1S)
            if [ $DDPlanting -ge 1327 -a $DDPlanting -le 1753 ]
            then
                GoOn=Yes
                break
            fi
        done
    fi
    if [ "$GoOn" = Yes ]
    then
        break
    fi
done

if [ "$GoOn" = Yes ]
then

    # GET THE WIND FIELD FOR THE VALLEY
    # First will need to create AFWIND input file.
    echo swill.ter > AFInput
    temp=`cat DateTrans.90 | grep " $Day " | cut -c8-13`
    # alt1date holds today's date
    alt1date=$temp
    DayOfMonth=`echo $temp | cut -c5-6`
    month=`echo $temp | cut -c3-4`
    year=`echo $temp | cut -c1-2`
    # Since we're using Greenwich time in AFWIND evening times in Oregon
    #   translate to early morning, next day in Greenwich. Therefore
    #   we need to move the date up by 1.
    if [ $DayOfMonth -eq 31 -a $month -eq 5 ]
    then
        DayOfMonth=1
        month=06
    elif [ $DayOfMonth -eq 30 -a $month -eq 6 ]
    then
        DayOfMonth=1
        month=07
    elif [ $DayOfMonth -eq 31 -a $month -eq 7 ]
    then

```

```

    DayOfMonth=1
    month=08
elif [ $DayOfMonth -eq 31 -a $month -eq 8 ]
then
    DayOfMonth=1
    month=09
else
    DayOfMonth=`expr $DayOfMonth + 1`
fi
echo $DayOfMonth >> AFInput
echo $month >> AFInput
echo "19$year" >> AFInput
# Mid-evening in Oregon = approx. 5 a.m. Greenwich
echo 5 >> AFInput
# hour = 5 a.m. ; minutes = 0 past 5 a.m.
echo 0 >> AFInput
# Now we need to see how many wind stations we have data available for
#    today. Possible = 3....Salem, Corvallis, Eugene
# Next "if" ensures dates used for weather lookups is in form
#    YYMMDD. ie. that day-of-month takes up two digits even if it is < 10.
if [ $DayOfMonth -lt 10 ]
then
    DayOfMonth="0$DayOfMonth"
    Prog=038
fi
alt2date="$year$month$DayOfMonth"
# Check up on Corvallis wind for this date and time
CvAvWind=`cat /home/ava/drapekr/weather/90_06-11.CVO|grep
$alt2date|awk '$3 > =
    300 && $3 < = 1200 {print}'|awk -F/ '$3 ~ /^[0-9][0-9][0-9][0-9]$/ {
print
    $3}'|GetWindAv`
CvAvDir=`echo $CvAvWind|awk '{print $2}'`
# All wind speeds are output in Meters/Minute
CvAvSpd=`echo $CvAvWind|awk '{print $1}'`
# Check up on Salem wind for this date and time
SlAvWind=`cat /home/ava/drapekr/weather/90_06-11.SLE|grep
$alt2date|awk '$3 > =
    300 && $3 < = 1200 {print}'|awk -F/ '$4 ~ /^[0-9][0-9][0-9][0-9]$/ {
print
    $4}'|GetWindAv`
SlAvDir=`echo $SlAvWind|awk '{print $2}'`
SlAvSpd=`echo $SlAvWind|awk '{print $1}'`
# Check up on Eugene wind for this date and time

```

```

EuAvWind=`cat /home/ava/drapekr/weather/90_06-11.EUG|grep
$alt2date|awk '$3 > =
300 && $3 <= 1200 {print}'|awk -F/ '$4 ~ /^[0-9][0-9][0-9][0-9]$/ {
print
    $4}'|GetWindAv`
EuAvDir=`echo $EuAvWind|awk '{print $2}`
EuAvSpd=`echo $EuAvWind|awk '{print $1}`
NumWindSites=0
if [ $CvAvSpd -ge 0 ]
then
    NumWindSites=`expr $NumWindSites + 1`
fi
if [ $SlAvSpd -ge 0 ]
then
    NumWindSites=`expr $NumWindSites + 1`
fi
if [ $EuAvSpd -ge 0 ]
then
    NumWindSites=`expr $NumWindSites + 1`
fi
# If the number of wind sites STILL is equal to zero use average
# wind vectors for all three sites and set NumWindSites equal to 3.
if [ $NumWindSites -eq 0 ]
then
    NumWindSites=3
    CvAvDir=308.
    CvAvSpd=224.
    SlAvDir=294.
    SlAvSpd=78.
    EuAvDir=272.
    EuAvSpd=66.
fi
if [ $NumWindSites -gt 1 ]
then
    echo 2 >> AFInput
    echo $NumWindSites >> AFInput
else
    echo 1 >> AFInput
fi
if [ $CvAvSpd -ge 0 ]
then
    # Give Afwind the Corvallis Location + Average Wind Speed & Direction
    echo 0 >> AFInput
    echo 42250 >> AFInput

```

```

echo $CvAvDir >> AFInput
# AFWIND wants wind speed in meters/sec and it must be >= 1
CvSpdPsec=`echo "$CvAvSpd / 60."|realmath`
if [ $CvSpdPsec -lt 1.0 ]
then
    CvSpdPsec=1
fi
echo $CvSpdPsec >> AFInput
fi
if [ $SlAvSpd -ge 0 ]
then
    # Give AFWIND the Salem Location + Average Wind Speed & Direction
    echo 23625 >> AFInput
    echo 88250 >> AFInput
    echo $SlAvDir >> AFInput
    # AFWIND wants wind speed in meters/sec and it must be >= 1
    SlSpdPsec=`echo "$SlAvSpd / 60."|realmath`
    if [ $SlSpdPsec -lt 1.0 ]
    then
        SlSpdPsec=1
    fi
    echo $SlSpdPsec >> AFInput
fi
if [ $EuAvSpd -ge 0 ]
then
    # Give AFWIND the Eugene Location + Average Wind Speed & Direction
    echo 6125 >> AFInput
    echo 0 >> AFInput
    echo $EuAvDir >> AFInput
    # AFWIND wants wind speed in meters/sec and it must be >= 1
    EuSpdPsec=`echo "$EuAvSpd / 60."|realmath`
    if [ $EuSpdPsec -lt 1.0 ]
    then
        EuSpdPsec=1
    fi
    echo $EuSpdPsec >> AFInput
fi
# Now to get cloud cover info (0=clear .. 8=overcast)
# Use Eugene Data, for cloud cover. Corvallis data is collected by
# machine and only goes up to 12000 feet. When Corvallis says clear
# it still may be overcast above 12000 feet. Eugene's data is hand
# entered; "clear" means clear.
CloudCovNum=0

```

```

CloudCovDen=`cat /home/ava/drapekr/weather/90_06-11.EUG|grep
$alt2date|awk '$3
    >= 300 && $3 <= 1200 {print}'|grep "CLR"|wc -l`
temp=`cat /home/ava/drapekr/weather/90_06-11.EUG|grep $alt2date|awk
'$3 >= 300
    && $3 <= 1200 {print}'|grep "SCT"|wc -l`
CloudCovDen=`expr $CloudCovDen + $temp`
temp=`expr $temp "*" 3`
CloudCovNum=`expr $CloudCovNum + $temp`
temp=`cat /home/ava/drapekr/weather/90_06-11.EUG|grep $alt2date|awk
'$3 >= 300
    && $3 <= 1200 {print}'|grep "BKN"|wc -l`
CloudCovDen=`expr $CloudCovDen + $temp`
temp=`expr $temp "*" 5`
CloudCovNum=`expr $CloudCovNum + $temp`
temp=`cat /home/ava/drapekr/weather/90_06-11.EUG|grep $alt2date|awk
'$3 >= 300
    && $3 <= 1200 {print}'|grep "OVC"|wc -l`
CloudCovDen=`expr $CloudCovDen + $temp`
temp=`expr $temp "*" 8`
CloudCovNum=`expr $CloudCovNum + $temp`
# if no cloud cover info, we'll assume clear as generic summer condition
if [ $CloudCovDen -eq 0 ]
    then
        CloudCov=0
    else
        CloudCov=`echo "$CloudCovNum / $CloudCovDen"|realmath`
    fi
CloudCov=`echo "$CloudCov + 0.5"|realmath`
CloudCov=`echo $CloudCov|sed 's/\.[0-9]*//`
echo $CloudCov >> AFInput
# Now to enter cloud type. 1=high,2=medium,3=low clouds.
# We will again use Eugene airport data to determine this.
AvCloudHt=`cat /home/ava/drapekr/weather/90_06-11.EUG|grep
$alt2date|awk '$4 >=
    300 && $4 <= 1200 {print $5}'|sed 's/[WEM]//'|DetCloudHt`
if [ $AvCloudHt -le 50 ]
    then
        echo 3 >> AFInput
    elif [ $AvCloudHt -gt 50 -a $AvCloudHt -le 150 ]
    then
        echo 2 >> AFInput
    else
        echo 1 >> AFInput

```

```

fi
# Now to get temperature...
AvEvTemp=`cat /home/ava/drapekr/weather/90_06-11.CVO|grep
$alt2date|awk '$3 >
300 && $3 <= 1200 {print}'|awk -F/ '{print $1}'|DetAv`
if [ $AvEvTemp -lt 0 ]
then
    MaxTemp=`cat hys90|grep $Day|cut -d' ' -f2`
    # The following equation is based on a regression of evening temps
    # versus maximum daily temps. r squared = .61.
    AvEvTemp=`echo "0.41 * $MaxTemp"|realmath`
    AvEvTemp=`echo "$AvEvTemp + 33.12"|realmath`
fi
echo $AvEvTemp >> AFInput
# ground moisture (1=dry, 2=wet)
Wetness=`cat /home/ava/drapekr/weather/CRVO90.PP|grep
"$month/$DayOfMonth"|cut -d" " -f2`
if [ $Wetness = --- ]
then
    Wetness=0
fi
if [ `echo "$Wetness -lt 0.1"|compare` -eq 1 ]
then
    echo 1 >> AFInput
elif [ `echo "$Wetness -gt 10.00"|compare` -eq 1 ]
then
    echo 1 >> AFInput
else
    echo 2 >> AFInput
fi
rm INPUT.DAT
rm WIND.OUT
rm MODIN.OUT
afwindOSU

## For each site ...
for site in `cat sites90|cut -d' ' -f1`
do
    if [ -f $$TasselingPlantings ]
    then
        rm $$TasselingPlantings
    fi
    # Get a list of plantings between 1st tassel and 1st silk

```

```

    for planting in `cat DamPlantings|grep $site|awk
'for(i=2;i<=NF;i++) print$i}'`
    do
        # determine the current corn stage of that planting
        DDPlanting=`expr $planting - $DDDiff`
        # if stage is between 1T and 1S....
        if [ $DDPlanting -ge 1327 -a $DDPlanting -le 1753 ]
        then
            echo $planting > > $$TasselingPlantings
        fi
    done

# Determine the trap catch for this date and site
Catch=`tail +2 trap90|grep $site|FindIt $Day 1 3`
# Don't do any of the calculations below UNLESS catch > 0
# AND unless there is at least one site between 1st Tassel and first silk.
if [ `echo "$Catch -gt 0.0"|compare` -eq 1 -a -f $$TasselingPlantings ]
then
    # Determine phenological stage of all plantings at site.
    # Determine relative likely concentration of moths
    for ThisPlanting in `cat AllPlantings|grep $site|awk
'for(i=2;i<=NF;i++) print
    $i}'`
    do
        # "DDThisPlanting" tells the phenological stage of the
        # planting in terms of cumulative DD from planting date.
        DDThisPlanting=`expr $ThisPlanting - $DDDiff`
        # File "CornData.90" has info on likely relative population sizes
        # of moth populations based on the phenological stage of the
        # corn planting. This is based on data from Johnson & Stinner
        ThisPop=`tail +2 CornData.90 | FindIt $DDThisPlanting 3 4`
        echo "$ThisPlanting = $ThisPop" > > RECLASS
    done
    r.reclass input=$site output=CEWPop.tmp < RECLASS
    rm RECLASS

# Determine the average wind vector
# 1st need to determine the location of this site
Easting=`cat sites90|grep $site|cut -d' ' -f2`
Northing=`cat sites90|grep $site|cut -d' ' -f3`
NorthDist=`expr $Northing - 4885000`
EastDist=`expr $Easting - 476375`
# Distance between wind vectors from AFWIND is 1195 meters.
# The following equations change from Northings and Eastings

```

```

# to "up" and "across" values to determine which vector is
# the most appropriate.
# (NOTE: 597.5 = 1195/2)
UpInt=`echo "$NorthDist + 597.5"|realmath`
UpInt=`echo "$UpInt / 1195"|realmath`
# Round out and produce an integer value...
UpInt=`echo "$UpInt + 0.5"|realmath`
UpInt=`echo $UpInt|sed 's/\.[0-9]*/'`
AcrossInt=`echo "$EastDist + 597.5"|realmath`
AcrossInt=`echo "$AcrossInt / 1195"|realmath`
# Round out and produce an integer value...
AcrossInt=`echo "$AcrossInt + 0.5"|realmath`
AcrossInt=`echo $AcrossInt|sed 's/\.[0-9]*/'`
# AFWIND puts the wind vector into the file WIND.OUT. NOW we'll
# need to determine how far down to go to get the x and y values
# of the wind vector from this file.
# NOTE: there are 74 wind vectors rows (North to South)
#       and 35 columns for a total of 2590 vectors.
NumPosDown=`expr $AcrossInt - 1`
NumPosDown=`expr $NumPosDown \* 74 + $UpInt`
SkipForX=`expr $NumPosDown + 3`
SkipForY=`expr $NumPosDown + 3 + 2590`
WindX=`cat WIND.OUT|awk "BEGIN {Num=0}
{ Num++
  if (Num == $SkipForX) {print; exit;}}"`
WindY=`cat WIND.OUT|awk "BEGIN {Num=0}
{ Num++
  if (Num == $SkipForY) {print; exit;}}"`
# WindX and WindY are in M/Sec ... switch to M/Min
WindX=`echo "$WindX * 60.0"|realmath`
WindY=`echo "$WindY * 60.0"|realmath`
# Most functions within this program see wind as a speed and a d
# direction, NOT as x, y coordinates. Need to convert....
temp1=`echo "$WindX * $WindX"|realmath`
temp2=`echo "$WindY * $WindY"|realmath`
WindSpeed=`echo "$temp1 + $temp2"|realmath`
WindSpeed=`echo "sqrt $WindSpeed"|realfunc`
# Except for five evenings, most evening winds in 1991 had
# speeds of less than 420 M/min. These are airport winds
# and are measured at approximately 10 M height. Winds at
# ground height surely are not as strong. Corn earworm moths
# are probably not able to fly much faster than 180 M/min.
# Assuming that moths don't partake in short range flight in
# winds faster than their flight speed, assuming that such

```



```

#   winds don't happen more than 5 times in a year I'll modify
#   the wind speed like so....
temp=`echo "$WindSpeed / 420"|realmath`
WindSpeed=`echo "$temp * 180"|realmath`
temp1=`echo "$WindY / $WindX"|realmath`
WindDir=`echo "atan $temp1"|realfunc`
# convert from radians to degrees...
WindDir=`echo "$WindDir * 57.29577951"|realmath`
WindDir=`echo "270 - $WindDir"|realmath`
WindDir=`echo "$WindDir + 0.5"|realmath`
WindDir=`echo $WindDir|sed 's/\.[0-9]*//'\`
# If wind speed is greater than 180 then assume moths are not
#   flying and don't calculate any further.
if [ $WindSpeed -le 180 ]
then
    # Set up likeliness of catch (LOC) surface
    #echo $WindSpeed|mkpgm > Like.pgm
    # LdLikeGrass $WindDir Like.pgm
    if [ $WindSpeed -ge 0 -a $WindSpeed -le 36 ]
    then
        zcat Like.18 > LIKELINESS
    elif [ $WindSpeed -ge 37 -a $WindSpeed -le 54 ]
    then
        zcat Like.54 > LIKELINESS
    elif [ $WindSpeed -ge 73 -a $WindSpeed -le 108 ]
    then
        zcat Like.90 > LIKELINESS
    elif [ $WindSpeed -ge 109 -a $WindSpeed -le 144 ]
    then
        zcat Like.126 > LIKELINESS
    else
        zcat Like.162 > LIKELINESS
    fi
    LdLikeGrass $WindDir LIKELINESS

    # Get the total sum of likeliness * population
    TotSum=`GetTotSum $site|grep TotSumIs|cut -d' ' -f2`
    # The sum over all days 1T to 1S of average
    #   likeliness values will be saved for
    #   each planting at each site (eventually).
    #   These will be used to standardize the
    #   calculated modified catches. The next
    #   couple of lines set up a file with the
    #   average likeliness values for today for

```

```

#    this site.
r.average base=$site values=Like.tmp result=AvLike.tmp
r.cats AvLike.tmp > AV.LIKE

# For each planting for which damage info is available
#   and for which the stage is between 1st tassel and 1st
#   silk.
for planting in `cat $$TasselingPlantings`
do
    # Use LOC and likely moth concentration to determine
    #   today's moth catch, then modify cumulative catch.
    # Get sum of Likeliness * Pop for this planting
    AvPlanting=`cat AVERAGE|grep "^$planting"|cut -f2`
    AvLikeliness=`cat AV.LIKE|grep "^$planting"|cut -f2`
    # Get the number of cells in this planting.
    CellsPlanting=`cat STATS|grep $planting|cut -d" " -f2`
    SumPlanting=`echo "$AvPlanting * $CellsPlanting"|realmath`
    Ratio=`echo "$SumPlanting / $TotSum"|realmath`
    CatchPlanting=`echo "$Ratio * $Catch"|realmath`
    # Need to add this catch to the current value
    #   for this site/planting in the "CumCatch" file
    cat CumCatch|sed "s/0 $site/1 $site/"|UpdateCum $planting
$CatchPlanting
    $Catch $AvLikeliness > Temp.CumCatch
    cat Temp.CumCatch > CumCatch
done
fi
fi
done
fi
Day=`expr $Day + 1`
done

if [ -f $$TasselingPlantings ]
then
    rm $$TasselingPlantings
fi

```

**File 2: UpdateCum.** This script file updates cumulative catch values in the data file "CumCatch".

```

awk '{ if ($1 == 1 && $3 == '$1')
      { v1 = $4 + '$2'
        v2 = $5 + '$3'
        v3 = $6 + '$4'
        v4 = $7 + 1
        print "0 " $2 " " $3 " " v1 " " v2 " " v3 " " v4 " " $8}
      else
        print "0 " $2 " " $3 " " $4 " " $5 " " $6 " " $7 " " $8}'

```

**File 3: pnmrot.** This script file rotates the likeliness of catch map surface created by "mkppm" by any desired angle. These map surfaces are output as ppm formatted files. The syntax of the program is "pnmrot <angle> <ppm file>

```

InFile=$2
Angle=$1

if [ $Angle -lt 0 ]
then
  Angle=`expr 360 + $Angle`
fi

if [ $Angle -ge 315 -a $Angle -lt 360 ]
then
  Temp=`expr $Angle - 360`
  pnmrotate -antialias $Temp $InFile
elif [ $Angle -ge 0 -a $Angle -lt 45 ]
then
  pnmrotate -antialias $Angle $InFile
elif [ $Angle -ge 45 -a $Angle -lt 135 ]
then
  Temp=`expr $Angle - 90`
  pnmflip -r90 $InFile | pnmrotate -antialias $Temp
elif [ $Angle -ge 135 -a $Angle -lt 225 ]
then
  Temp=`expr $Angle - 180`
  pnmflip -r180 $InFile | pnmrotate -antialias $Temp
elif [ $Angle -ge 225 -a $Angle -lt 315 ]
then
  Temp=`expr $Angle - 270`

```

```
pnmflip -r270 $InFile | pnmrotate -antialias $Temp
fi
```

**File 4: FindIt.** This script file functions as a database look-up utility for ascii files containing several columns of information. Given the value of one particular variable (the input variable), FindIt finds the value of a corresponding variable (output variable) as observed in some data file. For example it is used: 1) to look up the trap catch (output) given any particular day (input), 2) to look up the cumulative degree days (output) given any day (input), and 3) to look up likely moth population values (output) depending on cumulative degree days for the planting for which a moth estimate is desired (input). Syntax of Findit: "Findit <Input value> <column containing input variable values> <column containing output variable values> .

```
awk '{ if ($'2' >= '$1') {print $'3';exit;} }'
```

**File 5: GetTotSum.** This script file creates the contribution-to-catch map layer (Moth Population X Likelihood of Capture) and then sums the contribution-to-catch values for all pixels within any particular planting. Syntax: GetTotSum <Site> <Planting> .

```
# There are 5 map layers we'll be dealing with in this script file
#      #1) Moth Capture Likelihood (Like.tmp - temporary)
#      #2) Relative CEW Moth Pop   (CEWPop.tmp - temporary)
#      #3) Pop X Likelihood        (PopxLike.tmp - temporary)
#      #4) Average Pop X Likelihood (AV.tmp - temporary)
#      #5) Original Site Map       (permanent)
#
# Parameters Passed to this script are 1) Site and 2) Planting of interest

# 1st Create PopLike.tmp
echo "PopxLike.tmp = CEWPop.tmp * Like.tmp" | r.mapcalc
```

```

# Create AV.tmp
r.average base=$1 values=PopxLike.tmp result=Av.tmp

TotSum=0
r.cats Av.tmp > AVERAGE
r.stats -q -c $1 > STATS

# For every planting at this site ....
for SumPlanting in `cat AllPlantings|grep $1|awk '{for(i=2;i<=NF;i++) print $i}'`
do
    # Get the average value of likelinessXpop for this planting
    AvPlanting=`cat AVERAGE | grep "^$SumPlanting" | cut -f2`
    # Get the number of cells in this planting.
    CellsPlanting=`cat STATS | grep $SumPlanting | cut -d" " -f2`
    SumThisPlanting=`echo "$AvPlanting *" $CellsPlanting"|realmath`
    TotSum=`echo "$TotSum + $SumThisPlanting"|realmath`
done
echo "TotSumIs $TotSum"

```

## Appendix C: C programs accessed by Catch Modification Model Script File.

### File 1: mkpgm.c.

```

/* Programmer: Ray Drapek                                     */
/* Starting Date: 4/9/92                                       */
/* This is a program designed to create a "likeliness-of-catch" surface
for the 2.5 km area around a pheromone trap. Input values for the model
include wind speed, moth speed, and some time limit. The trap is assumed to
occupy the 0,0 position. Wind moves straight down the x axis. Moth
flight is assumed to result as a combination of two vectors, the moth
orientation and speed vector and the wind vector. The likelihood of finding
the trap is assumed to be theta/360 times xtra search time. Where theta is
the angle (in degrees) defined by the line from moth to trap and the line
from moth to furthest distance downwind. Xtra search time is one minus the
ratio of dist-from-xy-to-trap/max-dist-on-xy-trap-line. This version
prints PGM files which can be rotated within UNIX with "pnmrotate". */
#include <stdio.h>
#include <math.h>
#define pi 3.14159

double p(Main, Power)
double Main;
int Power;
{
    int ii;
    double temp;

    temp = 1.0;
    for(ii=1; ii < (Power + 1); ++ii)
        temp = temp*Main;
    return temp;
}

```

```

double CalcAngle(x, y, length)
double x, y, length;
{
    double a, b, angle;
    a = sqrt((x*x) + (y*y));
    b = sqrt(((x - length)*(x - length)) + (y*y));
    angle = acos(((a*a) + (b*b) - (length*length))/(2*a*b));
    return angle;
}

```

```

double CalcLike(time, Wind, Moth, x, y, MaxPlumeDist)
double time, Wind, Moth, x, y, MaxPlumeDist;
{
    double Dist, temp, Theta;
    double xMax, yMax, DistMax, Distxy, Xtra;
    double xMax1, xMax2;
    /* As a measure of how much excess time moth
       will have to search for plume, calculate
       the ratio of dist from moth pos to trap
       over maximum distance on that line that
       moth can reach trap within allotted time.
       us this ratio is an indication of
       how much extra search time the moth will
       have. */
    xMax = p(x,2)*p(Moth,2);
    xMax = xMax - p(y,2)*p(Wind,2);
    xMax = (time*sqrt(xMax + p(y,2)*p(Moth,2)))/x;
    xMax1 = ((-1*Wind*time) + xMax)/((p(y,2)/p(x,2)) + 1);
    xMax2 = ((-1*Wind*time) - xMax)/((p(y,2)/p(x,2)) + 1);
    if ( (xMax1*x) > 0 )
        xMax = xMax1;
    else
        xMax = xMax2;

    yMax = (y/x)*xMax;

    DistMax = sqrt(p(xMax,2) + p(yMax,2));
}

```

```

    Distxy = sqrt(p(x,2) + p(y,2));
    if(DistMax < Distxy)
        Xtra = 0.0;
    else
        Xtra = 1 - (Distxy/DistMax);

    Dist = MaxPlumeDist;

    /* Calc angle between line from moth to trap
       and line from moth to farthest downwind
       plume position. */
    Theta = CalcAngle(x,y,Dist);
    temp = Xtra*(Theta/(2*pi));
    return temp;
}

/***** M A I N *****/
main()
{
    int i, j;
    double time, Wind, Moth, x, y, MaxPlumeDist;
    double RealLike, MaxRealLike;
    int Like;

    /* Time and Distance units can be anything as long as they are consistant.*/
    /* However, the measurements assigned below assume time units of minutes */
    /* and distance units of meters. */
    scanf("%lf", &Wind);
    /* Wind = 150.0; */
    time = 16.0;
    Moth = 180.0;
    MaxPlumeDist = 25.0;

    printf("P2\n");
    printf("500 500\n");
    printf("250\n");

    for(i=1; i < 501; ++i)
    {
        for(j=1; j < 501; ++j)
        {

```



```

        if ( Wind > Moth )
            printf(" 0");
        else {
            x = (10*i)-2505;
            y = (10*j)-2505;
            if (sqrt((x*x) + (y*y)) <= 2500)
            {
                RealLike = CalcLike(time, Wind, Moth, x, y, MaxPlumeDist);
                Like = RealLike*500;
                printf(" %i",Like);
            }
            else
                printf(" 0");
        }
    }
    printf("\n");
    exit(0);
}

```

## File 2. GetWindAv.c.

```

/* Programmer: Ray Drapek                                     */
/* Date: 6/22/92                                              */
/* Program reads in variable numbers of wind data and outputs the average */
/* wind vector. Inputted wind data is in the formate DDSS where DD is the */
/* wind direction in tens of degrees (ie. 31 = 310 degrees) and SS is wind */
/* speed in knots. */

#include <stdio.h>
#include <math.h>

main()
{
    int dir, speed;
    float Rdir, Rspeed;
    int InputVal;
    int N;
    float x, y, sumx, sumy, avx, avy, AvSpeed, AvDir;

```

```

sumx = 0.0;
sumy = 0.0;
N = 0;
for ( N = 0; scanf("%d", &InputVal) == 1; ++N) {
    /* printf("InputVal = %d\n",InputVal);*/
    dir = InputVal/100;
    speed = InputVal - (100 * dir);
    Rspeed = speed * 30.864;
    /* printf("Rspeed = %f\n",Rspeed);*/
    /* Convert speed from knots to m/min */
    /* We get dir info in terms of direction wind is FROM and in terms of */
    /* the degrees off of north. We want to convert to direction TO and */
    /* to degrees off of due east. */
    /* ALSO we will convert degrees to radians. */
    Rdir = 0.017453293 * (270 - (10 * dir));
    /* printf("Rdir = %f\n",Rdir);*/
    x = cos(Rdir) * Rspeed;
    y = sin(Rdir) * Rspeed;
    /* printf("x, y: %f, %f\n",x,y);*/
    sumx = sumx + x;
    sumy = sumy + y;
}
if ( N > 0 ) {
    /* printf("sumx = %f, sumy = %f, N = %d\n",sumx,sumy,N); */
    avx = sumx/N;
    avy = sumy/N;
    AvSpeed = sqrt((avx*avx) + (avy*avy));
    printf("%f", AvSpeed);
    if (avx < .0001 && avx > -.0001)
        if (avy >= 0)
            AvDir = 4.712388980;
        else
            AvDir = 1.570796327;
    else
        AvDir = atan(avy/avx);
    if (avx < 0)
        AvDir = AvDir + 3.141592654;
    /* Convert Angle Back from radians to degrees */
    AvDir = 57.29577951 * AvDir;
    /* Convert Back to Angle off of north */
    AvDir = 270 - AvDir;
    printf(" %f",AvDir);
}

```

```

else
    printf("-9999999.9 -99999999.9");

    exit(0);
}

```

### File 3. RealFunc.c.

```

/* Programmer: Ray Drapek */
/* Date: 6/02/92 */
/* Program to perform standard c functions such as cos, sin, etc.*/
/* to a single variable input. */

#include <stdio.h>
#include <string.h>
#include <math.h>

main()
{
    int i;
    float x, result;
    char c, function[6];

    for(i=0; (c=getchar()) != ' '; ++i)
        function[i] = c;

    function[i] = '\0';
    scanf("%f",&x);
    result = 0;

    switch (function[0]){
    case 'a':
        switch (function[1]){
        case 's':
            result = asin(x);
            break;
        case 'c':
            result = acos(x);
            break;
        case 't':

```

```

        result = atan(x);
        break;
    };
    break;
case 'c':
    switch (function[3]){
    case '\0':
        result = cos(x);
        break;
    case 'h':
        result = cosh(x);
        break;
    case 'l':
        result = ceil(x);
        break;
    };
    break;
case 'e':
    result = exp(x);
    break;
case 'f':
    switch ( function[1] ){
    case 'l':
        result = floor(x);
        break;
    case 'a':
        result = fabs(x);
        break;
    };
    break;
case 'l':
    switch (function[3]){
    case '\0':
        result = log(x);
        break;
    case '1':
        result = log10(x);
        break;
    };
    break;
case 's':
    switch (function[3]){
    case '\0':
        result = sin(x);

```

```

        break;
    case 'h':
        result = sinh(x);
        break;
    case 't':
        result = sqrt(x);
        break;
    };
    break;
case 't':
    switch (function[3]){
    case '\0':
        result = tan(x);
        break;
    case 'h':
        result = tanh(x);
        break;
    };
    break;
}

printf(" %f", result);
exit(0);
}

```

#### File 4. RealMath.c.

```

/* Programmer: Ray Drapek
/* Date: 6/02/92
/* Program to perform comparisons of real numbers

#include <stdio.h>
#include <string.h>

main()
{
    float x, y, result;
    char operation;

    scanf(" %f %c %f", &x, &operation, &y);

```

```

result = 0;

if ( operation == '*' )
    result = x*y;
else if ( operation == '+' )
    result = x + y;
else if ( operation == '/' )
    result = x/y;
else if ( operation == '-' )
    result = x - y;

printf("%f", result);
exit(0);
}

```

### File 5. Compare.c.

```

/* Programmer: Ray Drapek
/* Date: 6/02/92
/* Program to perform comparisons of real numbers

#include <stdio.h>
#include <string.h>

main()
{
    float x, y;
    int result;
    char relation[4];

    scanf("%f %s %f", &x, relation, &y);
    result = 0;

    if ( strcmp(relation, "-lt") == 0 ) {
        if ( x < y )
            result = 1;
    }
    else if ( strcmp(relation, "-le") == 0 ) {
        if ( x <= y )
            result = 1;
    }
}

```

```
    }  
    else if ( strcmp(relation, "-gt") == 0 ){  
        if (x > y)  
            result = 1;  
    }  
    else if ( strcmp(relation, "-ge") == 0 ){  
        if (x >= y)  
            result = 1;  
    }  
    else if ( strcmp(relation, "-eq") == 0 ) {  
        if (x == y)  
            result = 1;  
    }  
  
    printf(" %d", result);  
    exit(0);  
}
```